Commentary

ECONOMIC POTENTIAL OF MALAYA

MALAYA's economic potential depends on population trends, on the opening up of new land, on the opportunities for industrialization, and perhaps most of all on the price of natural rubber. The development of the population, and indeed many of Malaya's political and economic problems, can be related to migrations during rubber booms, the great depression, the Sino–Japanese war, and during the Japanese occupation[1].

The death rate is falling steadily, and although the birth rate has dropped slightly there is a natural rate of increase of population of about 3·5 per cent per year in Singapore and 3·3 per cent in the Federation of Malaya, with a tendency for the two rates to approximate to one another. Between the 1947 and the 1957 censuses there appears to have been also a migration of about a quarter of a million people from the Federation of Malaya to Singapore. This is no doubt a result of higher standards of living in Singapore.

Large natural population increases greatly affect the proportion of dependants to workers. The 1957 census results showed 619,104 persons under 15 years and 55,337 of 60 and over in Singapore whereas there were 771,488 between 15 and 60, *i.e.* 46·6 per cent were in the dependant age groups[2,3]. Corresponding results for the Federation of Malaya have not yet been published but are probably comparable. The age group 12 to 16 was quite abnormally small in the 1957 census; these were the children born during the Japanese occupation. *Table 1* illustrates the position in Singapore. Figures for the Federation of Malaya are not yet available but will no doubt reflect the same influences.

Table 1

Age	*Number of persons*
8 and under 12	149,767
12 and under 16	93,489
16 and under 20	111,761

Source: Legislative Assembly, Singapore, 1957. Census Preliminary Release No. 5.

We may conclude from these figures that the burden of dependency will increase rapidly during the next few years. The figures have a bearing also on the problem of unemployment; for about four years from 1957 the number of young people coming on to the labour market will be abnormally small. The real problem will begin in 1961.

If we are to attempt to anticipate Malaya's capacity to expand its economy we must try to relate this population to its natural and man-made resources; and this involves some classification of the population. Taking a total population, for the Federation of Malaya only, of six millions in 1955, the last year in which a rough analysis of employed workers was taken[4], and applying the Singapore proportions for dependants, there were probably about 1,600,000 male workers. About three-quarters of a million of these appear to have been engaged in agriculture, fishing, logging or farming, not counting the employees on large estates. This represents an increase of approximately a quarter since 1947, corresponding to the increase in the population as a whole.

Statistics for the rural areas are unreliable, but there appears to be little change in the area cultivated, whilst the output of rice, fish, vegetables, etc. has more than kept pace with the increasing population. Such a situation has, as could be expected, been accompanied by a relative change in earnings, the proportion of the agricultural income accruing to land increasing, and that to labour decreasing.

The failure to develop land rapidly enough to keep pace with the growth of rural population has had several causes: the Emergency which made those formerly cultivating the jungle fringes move to safer places, and also hampered road development; constitutional difficulties arising from control of land policy by the States and of finance by the Federation, making long term policy very difficult even if State administration, hampered by the Emergency and loss of staff, had been able to carry it out; and finally the rubber replanting scheme[5].

Because of the need to encourage replanting by the rubber industry, with modern high yielding material, extra taxation has been levied on rubber exports and the proceeds used to finance replanting.

For estates it was considered necessary to give subsidies only for replanting and not for new planting if large areas were not to go derelict. But with small-holdings there is in fact no economic reason for insisting on the same land being used. In view of the land shortage, even where estates are concerned, there should be no fear of areas of derelict land in regions where transport and services already exist. However, a policy based on this unfounded fear of vast areas of derelict land has been allowed to conduce one with even less economic justification, namely that of requiring small-holders to cut out their holdings so as to qualify for a grant for replanting[6]. Fortunately, although these restrictive provisions are still in force for the replanting grant, an additional scheme has now been introduced for subsidizing new rubber planting with high yielding material by small-holders.

Considerable progress has also been made in the last two years towards increasing land development in other ways. A Land Development Authority has been set up, with independent status and borrowing powers, to initiate land development projects. The first, at Ayer Lanas on the Thai border has reached the stage of collecting the Government grant for new planting of rubber and is beginning to repay a part of its debt[7]. Private capital formation occurs whenever a new feeder road is opened up by the Government and land is released for cultivation. The chief obstacles to development are delays in developing new roads, and delays in alienation of land. A grant from the United States, under the Colombo Plan, is being used in part to remedy the lack of feeder roads mentioned in the International Bank Mission Report[8]. Delays in the alienation of land, mainly as a result of administrative inadequacies of State Governments, are a more difficult problem.

Under the new Constitution, research and surveys in relation to land policy can be carried out by the Federal Government. With adequate research and drive in training programmes the problem of achieving adequate development of the rural economy could be overcome. But it is difficult to be optimistic about the prospects. To keep pace with population increase and make any perceptible progress in raising living standards and overcoming the land shortage about three hundred and fifty square miles of new land for small-holders must be opened up each year. This would not appear to be an impossible task, either financially or in terms of available land. The shortage is of research workers and of administrative and technical personnel to supervize and carry out new developments, including the all-important training of settlers. The development of small farms is clearly the most important need of the economy; the income:capital ratio should be the highest, and it is the most important field on political and social grounds.

Population is, however, increasing even faster in other sections of the community and new employment, which will need generally more capital per head, will be required in the urban areas also. Government encouragement to trade union organization is likely to ensure that wage levels in the more developed sector of the economy will remain appreciably above earnings in the rural areas, even if substantial unemployment develops. Indeed, if wages were to fall too far in rubber, tin, and in the European-owned industries, the effect on Malaya's national income might be harmful. The increased profits could, of course, be invested in Malaya, but this does not always happen and profits of such undertakings are therefore only in a restricted sense income available for investment in Malaya.

High wages in these industries, tend to cause high wages in Malayan-owned industries also and thus diminish the amount of local savings. A higher rate of industrial growth might be achieved by lower wages and higher export duties; but beyond a certain point low wages would reduce local demand to a level at which it might be difficult for the Government (within the general framework of a private enterprise economy) to achieve the necessary rates of investment.

Attention has therefore been focused on the need to attract foreign capital. The Prime Minister's proposed charter for foreign capital has attracted widespread interest and the pioneer industries scheme, with income tax relief and possibilities of tariff protection, is already attracting a steady flow of foreign capital. This inflow is not likely to encounter the usual difficulty of shortage of foreign exchange to service debts or permit remittance of profits; the increase in the output of rubber by between a quarter and a third, which may be expected from the replanting scheme, is likely to improve exports materially, while the pioneer industries themselves will tend to reduce the propensity to import.

On the other hand there is a real risk that high exports plus a large inward flow of capital will generate inflationary pressures that will strain local resources. There should be no shortage of crude labour but it may be very difficult to increase the numbers of local skilled personnel fast enough; and if this is not done, rising prices of other goods will bring in imported substitutes, so that other

lines of production will fall off in place of the pioneer industries.

One way in which this danger can be averted is by increased local saving, or Government surpluses; another is by suitable educational expansion. The establishment of a Central Bank in Kuala Lumpur is designed to introduce more order into the local banking system, reduce the influence of overseas banks, and build up a local money market[9,10]. But an improvement in local long term lending institutions (as foreshadowed in the expanded Singapore Industrial Promotion Board) and a raising of the standard of the rudimentary local share market, are needed to accelerate the trend towards increased purchase of shares by local investors.

Discussions of educational policy have mainly concentrated on language issues, and the problem of creating a Malayan nation. In face of a severe shortage of teachers drastic measures have been taken to increase enrolment in the Federation from 270,000 in 1946 to over four times this figure at the time of writing. These measures have included multiple sessions in many schools and the establishment of two teacher-training colleges in the United Kingdom, to which selected Malayan students were sent for training. In Singapore also there has been a sensational increase in school enrolment from about 80,000 in 1946 to over 290,000 in 1958.

The achievement has been extraordinary, but has left little time for consideration of the economic problems involved. Expenditure on education exceeds 4 per cent of the national income in Singapore and approaches 3 per cent in the Federation. The economic problem of raising the level of literacy in a country with Malaya's demographic structure is inevitably difficult. Where educated people are scarce an adequate salary is inevitably high in relation to the national average income; and where children are as numerous as in Malaya this adds to the teaching load and also reduces the number of female workers in the working age groups.

The situation is being met by allowing large disparities of standards between urban and rural areas, and between English-medium and vernacular-medium schools, to continue. But this is leading to totally inadequate selection of the best candidates from sources outside the English schools, for higher education and technical skills. Research in linguistics, educational testing and adult education techniques is badly needed to overcome these problems.

This is by no means the only line of research which is suffering from the acute staff shortages in Government, as a result of independence and rapid economic growth. The University is experiencing acute difficulty in establishing a local research tradition, because the best candidates simply cannot afford to lose seniority by undertaking research when the prospects for advanced training and rapid promotion in Government service are so good.

Rapid further expansion of the civil service, as a result of population growth and economic development, is likely in the next few years. But the acute need arising from the simultaneous replacement of hundreds of European civil servants is now past. Moreover the successful development of secondary schools since the war is now producing a rapid increase in the undergraduate population both in Singapore and in Kuala Lumpur. A few more years may be needed before the adequate supply of M.A. and M.Sc. candidates is forthcoming. But there is a good long term prospect that the need for research will be met.

T.H.S.

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AGRICULTURAL RESEARCH IN MALAYA

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The research on some aspects of Malayan agriculture is outlined. This includes soil surveys on both developed and undeveloped areas and plant nutrition studies on various crops by means of leaf analysis, sand culture and fertilizer trials. The progress of breeding and selection work on rice, oil palms and coconuts is given and the more serious diseases and pests of Malayan crops are described and their control discussed.

MALAYA has an area of 51,200 square miles of which about eighty per cent is still under jungle. The total population (1957 census) of the Federation was 6·3 million. Of the 41,000 square miles of undeveloped land, there are possibly 3,000 square miles of peat swamps of limited agricultural potential[1]; while in the northern part up to eighty per cent of the undeveloped land may be too steep for agriculture. A rough estimate gives something of the order of 16,000 square miles topographically suitable for agriculture.

Agricultural research in Malaya is directed towards mapping those areas which are suitable for agriculture, finding new crops to diversify the economy, which at the moment so largely depends on rubber (*Table 1*) and increasing the output of the present agriculture by the use of fertilisers, improved varieties and control of pests and diseases.

Table 1. Acreage and value of the more important crops in Malaya (1957)

Crop	*Acreage*	*Exports (value in* (M) $\$ \times 10^6$)
Rubber	3,520,000	1,050·5
Coconuts	517,000	27·3
Oil palms	116,000	48·8
Pineapple	45,500	26·5
Rice	901,000	−142·0 (Net import)

There have never been adequate staff or funds to undertake fundamental or long range research and most of the resources have had to be devoted to day to day problems of an *ad hoc* nature. Such work has produced useful results but future progress will be severely handicapped by the lack of fundamental information. The department is trying to carry out a certain amount of fundamental research and at the same time undertake a programme of short range research, for immediate practical application.

Soil Research

During the past few years a major development has been the initiation of soil surveys on a large scale. The greater part of the work has been concentrated on surveying areas of potential agricultural value, which are now under jungle (*Figure 1*). This work has been greatly aided by the availability of reasonably accurate topographical maps, produced on a scale of one inch to one mile for emergency purposes and largely based on aerial photographs.

Soil surveying without adequate base maps is an almost impossible task under Malayan conditions. Surveys have been carried out in swamp areas to find land suitable for rice and on the sedentary soils to delineate areas suitable for development of various crops. Maps are usually made on a scale of one inch to one mile and so far about 190,000 acres have been surveyed[2,3]. A recent development is the production of schematic soil maps on a scale of 1:500,000 which are built up largely from existing geological and topographical information combined with soil information from road and track traverses. These maps will be used for overall planning of agricultural development. In developed rice areas detailed maps on a scale of $2\frac{1}{2}$ inches to one mile have been made and these are used for the siting of manurial experiments.

Detailed examination of numerous soil profiles has shown that, while the parent material determines the colour and structure of the soil profile, the soil nutrients show little variation. It has been concluded that the intense leaching by the heavy rainfall (100–150 inches p.a.) is responsible for this levelling out effect. All sedentary soils in Malaya are extremely low in exchangeable bases; for example soils in Ghana, developed over similar parent material, but under a rainfall of about 60 inches per year, have ten times as much exchangeable calcium in the top layer as Malayan soils.

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Figure 1. A soil survey party in a jungle camp

Plant Nutrition

In conjunction with the work on soil survey, studies of plant nutrition are being undertaken. These include soil and plant analyses, pot experiments with both soil and sand and field experiments. In general, analysis of tropical soil is of little value for determining the nutrient needs of crops because none of the methods generally in use have been designed for tropical soils but are adaptations from methods used in temperate soils. Thus, considerable attention has been devoted to leaf analysis as a means of determining the nutrient status of plants. Methods have been worked out for oil palms[4] and work on leaf analysis of padi, coconuts and cacao has been undertaken. Pot experiments are carried out in order to determine the nutrient status of the different soil series located during soil surveys. Though care is obviously needed in applying the results of pot experiments to field conditions nevertheless such tests do give useful indications.

During the past few years considerable work has been done on the growing of rice and cacao in sand culture to determine major and minor element deficiency symptoms in these plants[5,6] (*Figure 2*). As well as simple deficiency and toxicity symptoms, a study of the interactions of the various nutrients in the growing of rice was carried out. This was done because of the presence in Malaya of a physiological disease, *penyakit merah* literally 'red sickness', which was thought to be due to the interaction of two or more nutrients.

This sand culture work has shown that cacao is extremely susceptible to calcium deficiency while oil palm has an extremely low calcium requirement and flourishes on soils with low calcium levels, where cacao shows severe deficiency symptoms (*Figures* 3 and *4*). On the other hand, the oil palm has a high magnesium requirement. Cacao is also very susceptible to zinc deficiency and deficiency symptoms are extremely easy to produce in sand culture. It can, however, survive under conditions of very low manganese supply for long periods. In the absence of iron rice will die almost as quickly as when the nitrogen supply is withheld. Its requirements for manganese are also high but there appears to be only a small margin between sufficiency and toxicity, since manganese toxicity symptoms readily appear. On the other hand it is possible to use very high concentrations of iron in culture solutions without ill-effect.

Field manurial trials have been carried out on a number of crops including fruit, coconuts and padi. Those on padi have been the most extensive and until fairly recently such trials were carried out at agricultural stations. However, it was realized that the conditions were far from typical of those in cultivators' fields and many trials are now carried out in the farmers' fields. In such trials there is only one replication at each point, but replications are scattered at random throughout an area. The trials are carried out in conjunction with soil surveys and a number of the replicates are put down in one soil series. Other work on rice has shown that

yields can be increased considerably by nursery manuring and by transplanting seedlings of the correct age at the proper spacing.

Plant Breeding and Selection

The improvement of yields by selection and breeding is one of the cheapest and most reliable methods of increasing production. The department has programmes for improvement of rice, cacao, oil palms, coconuts, fruits and tea.

Rice

Nearly all the rice grown in Malaya is of the *indica* variety which is characterized by an extreme photosensitivity. The main rice growing area lies between latitude 6° 40′ N and latitude 2° 10′ N, but there are very many varieties within this area. The difference in day length between the longest and shortest day at Alor Star in the north is 40 mins and at Malacca in the south it is 14 mins. Any programme for varietal improvement must include a large number of varieties so that selection is a more complicated and longer term problem than in countries where the varieties do not have this sensitivity. Recent work on this problem in Malaya, in which a considerable number of varieties were sown at different latitudes in every month of the year, showed that large differences in time to ear emergence or maturation in rice can be induced by very small differences in natural day length. Sowings made between December and March give long times to ear emergency while sowings made between August and October give the minimum times.

To date, selection work has been confined almost entirely to improvement of yields within established varieties[7,8,9] but hybridization of non-photosensitive *japonica* types with the *indicas* is now under way. The combination of the short maturation period and responsiveness to high fertility of the *japonica* varieties with the non-glutinous quality of the *indicas* should give a short term variety suitable for two crops per year.

Little work has been done on breeding for resistance to pests and diseases. Some of the more serious diseases of rice in other countries are not too serious in Malaya, *e.g.* many varieties are fairly resistant to *Piricularia oryzae*. *Helminthosporium oryzae* is the commonest disease of padi and may cause considerable reductions in yield. As regards pests, the most serious are undoubtedly the various species of stem borer. *Oryzae ridleyii*, a perennial rice with a solid stem has been crossed with *Oryzae sativa* in an attempt to breed a resistant variety, but this has not been successful.

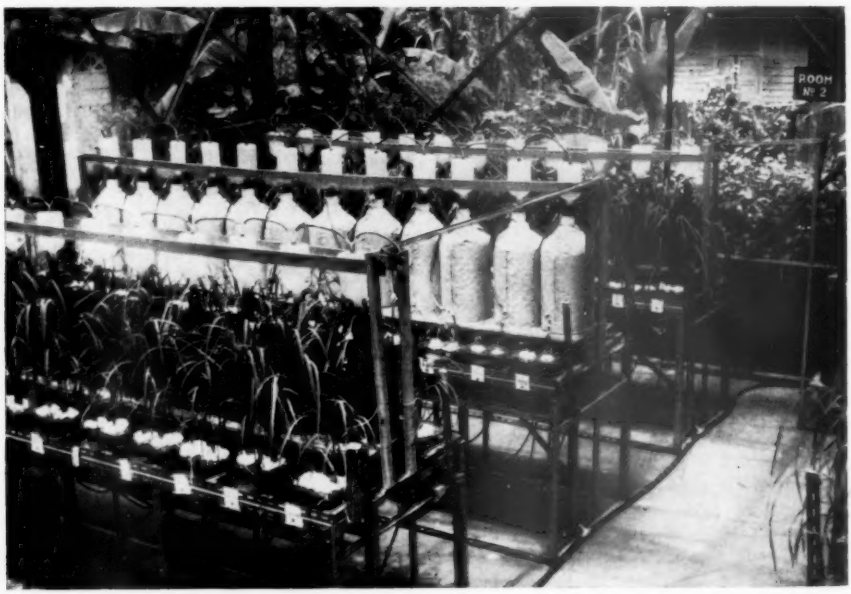

Figure 2. A semi-automatic nutrient supply system for growing rice in sand culture

Oil Palm

The oil palm[10] gives by far the highest yield of oil per acre of any crop and there are areas in Malaya capable of yielding two tons of oil per acre. Attention in the past was centred on the 'dumpy' palm, but extensive experiments have now shown that the dumpy habit is associated with slow growth and lateness of bearing and these are serious drawbacks. Attention is now being concentrated on the production of *tenera* palms, in which the kernel has a very thin shell and which contain 23 to 24 per cent of oil in the fresh fruit bunch compared with the 16 to 18 per cent in normal *deli* dura palms. *Tenera* material is produced by crossing the thick shelled dura palms with the shell-less *pisifera* type.

Coconuts

Like the oil palm the coconut cannot be propagated vegetatively and breeding is again a very long term project. In addition, one oil palm bunch may contain an average of 600 seeds and one palm may produce up to 10 bunches per year whereas a coconut palm will produce at the most 150 nuts p.a.

Work on coconuts was started by the department in the 1920's and nuts from high yielding palms from many different parts of the world were obtained as foundation stock. These were planted out in a station, and nut number, weight of meat and percentage of oil was recorded for over twenty years. These palms are now being used for selfing and crossing. Unfortunately the number of seedlings is so small that nursery selection, which is known to be important, is difficult.

Pests and Diseases

All crops in Malaya are attacked by at least one pest or disease and although losses are undoubtedly great they are not usually spectacular.

Stem borers are a serious pest of rice and in some areas up to 50 per cent of the tillers may be bored[11]. Stem borers are a problem in all rice growing countries but in Malaya the problem is complicated, since stem borers are most serious in areas where fish are an extremely important part of the cultivators' livelihood and many of the modern insecticides are toxic to fish. Four species of stem borers are of importance in Malaya, but there are indications that *Chilotraea polychrysa* and *Schoenobius incertulas* cause the most damage.

In recent years a survey of stem borer damage has been carried out in many areas of the country and a detailed investigation of the life cycle of *Chilotraea* has been completed. Certain insecticides, *e.g. Parathion*, will attack the stem borer while it is actually in the stem but such an insecticide is extremely dangerous since protective clothing cannot be worn. New insecticides, particularly the less toxic phosphorus compounds are now being tried out. The use of certain *Tachinid* flies as parasites on stem borers was also tried, but unsuccessfully[12].

Figure 3. Poor cacao on a granite derived soil. This plant is suffering from both Ca and Zn deficiency

Another pest which causes very considerable damage is the Rhinoceros beetle of coconuts, *Oryctes rhinoceros*. This insect breeds mostly in dead wood, *e.g.* coconut stems and the refuse at saw mills. The problem has been aggravated by the extensive replanting of rubber in which the old rubber is often poisoned thus forming ideal breeding grounds. So far no successful method of chemical control has been evolved and the only control possible is by eliminating the breeding sites and manual picking of the beetle from young coconuts. Attempted control by trap breeding pits has been unsuccessful.

Other pests which assume importance, though usually confined to localized outbreaks, are; the bagworm of oil palm, *Cremastopsyche pendula* which has been fairly well controlled by aerial spraying; the fruit borer in citrus for which there

Figure 4. A well grown five year old oil palm on the same soil as the cacao in Figure 3

is really no effective control; the clove borer, controlled by gammalin; and *Valanga nigricornis* on cover crops such as *Crotolaria*. The mosquito bug *Helopeltis* has caused damage on cacao and tea but can be controlled by fogging with D.D.T. Various types of sucking bugs on rice, *e.g. Leptocorisa acuta*, which feeds on the milk ripe grain, and *Scotinophora coarctata*, which feeds at the base of the plant, sometimes occur in quite severe local outbreaks but they also are relatively easy to control by fogging.

Fortunately none of the diseases are of overwhelming importance. The arrival of blister blight (*Exobasidum vexans*) on tea a few years ago posed serious problems, but can be effectively controlled by copper sprays. Some work has been carried out on the effectiveness of different copper fungicides while other investigations have shown that more dilute sprays or increasing the interval between sprayings can be used to reduce cost[13].

Several diseases of rice are present in Malaya, some occurring every year in most padi areas while others are more sporadic[14]. Some of the more serious diseases, *e.g.* blast, *Piricularia oryzae*, though found in Malaya, are usually not serious and several of the Malayan varieties are reasonably resistant to it. Experiments on seed dressing have shown little benefit when fresh seed giving a high percentage germination was used.

A recent discovery of a type of 'wilt' on coconuts in certain areas caused concern since it was feared it might be one of the serious diseases found in other coconut areas. Early symptoms of the disease are the shedding of nuts, the bending of the fronds near the base and the drying out and wilting of the outer leaves. Progressively younger leaves wilt and die and the size of the remaining leaves is reduced. Ultimately only a few green leaves are left upright in the crown and eventually they also die and the bud disintegrates, becoming affected by a soft, evil-smelling bacterial rot. Progress of the disease is said to be rapid, death occurring within six months of the first appearance of abnormal symptoms. This is a disease of mature palms, infection not occurring until the plants are over 20 years of age[15]. The disease only spreads very slowly and records of blocks of palms show that only one or two palms in a large block may become affected in a year.

Fruit Preservation

Other activities of the Department of Agriculture include research on the quality of various Malayan fruits and their preservation. Fruits on which this work has been carried out include rambutan (*Nephelum lappaceum*), mandarin orange, guavas (*Psidum guajava*) and durian (*Durio zibenthus*). Such work is of importance not only for building up export markets but also as a means of disposing of the seasonal glut of fruit from the expanding fruit growing industry. Attempts are being made to find cheap methods of fruit preservation, *e.g.* sun drying, and also simple methods which can be used by the housewife.

Apart from the research work carried out by the Research Branch of the Department of Agriculture at least half its efforts are devoted to provision of advisory services both for the public and for the extension services of the Department.

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Second Prize in the Waverley Gold Medal Essay Competition

THE GENERATION OF DIRECT CURRENT AT HIGH POTENTIALS

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The author emphasizes the need for a medium energy machine of high power for use in nuclear research, and he describes a small ionized gas flow high voltage generator to give a direct current at high potential. Various possible applications for such an apparatus are suggested.

SINCE Roentgen's discovery of x-radiation it has been known that many effects are produced by the interaction of atomic particles with matter and the continual investigation of these phenomena has developed into a vast research project. Since the type of reaction is dependent upon the energy of the particle it became imperative from the earliest days to devise machines capable of producing particles with larger and larger energies, and the design of these machines has itself become a large and costly project.

Initially work was conducted at low potentials and currents of electrons of the order of amps were passed through gases. Owing to limited power supplies it was necessary to operate at lower current as the potential was increased and the production of an almost steady d.c. supply may be said to have reached its peak potential in the Van de Graaff generator capable of delivering about one milliamp of charged particles at six million volts. The quantity of information yielded by this line of approach has been extraordinary and has tended to overshadow those properties of matter not readily investigatable by this method.

All high energy machines so far devised have one common failing—the output power is quite low. This may be interpreted as stating that the number of particles obtainable is only sufficient to investigate those reactions having a relatively high probability. The advent of the nuclear reactor and atomic power production radically changed this outlook. Here was a device concerned with nuclear reactions on a hitherto unprecedented scale. High neutron fluxes became the order of the day.

It has now become commonplace to devise assemblies of material which yield large fluxes of neutrons, and with the expansion of thermonuclear research attempts are going on all over the world to produce even larger fluxes of electrons and deuterons. A large section of nuclear research is developing around high powered machines as distinct from those giving only high energy.

The prime requirement for this type of work is a medium energy machine of high power capable of producing charged particles in steady streams of accurately defined energy or in very high powered pulses. The purpose of this article is to describe apparatus which with little development could possess these features and in addition would be comparatively cheap to construct.

Direct Current at High Potential

There are two main methods in use today—the Cockcroft–Walton and the Van de Graaff machine. The Cockcroft–Walton generator is composed of a series of voltage-doubling circuits using rectifiers and is fed with alternating current. Fairly large currents are obtainable—about 10 mA, but the maximum potential obtainable is around 1 MV. It is not possible to draw large currents from the machine if accurate work is being performed due to a.c. ripple appearing on the output voltage.

The Van de Graaff machine acquires its potential by means of a moving insulator or belt which carries charge from a corona discharge up the potential gradient into a collecting sphere. This system is extremely stable and lends itself to accurate control of the potential up to 6 MV but the current is very

Figure 1. Mr W. E. Bennett with a 15 cm 80 kV single stage generator. He joined the Atomic Weapons Research Establishment in 1954 and has since worked on radiation measurement and electron accelerator techniques. (Reproduced by courtesy of the Director of A.W.R.E., Aldermaston)

limited, being often 50 to 100 μA, and 1 mA in the largest multi-belt machines. This limitation on current is due to the limited charge density it is possible to apply to the surface of the belt before breakdown to the surrounding gas occurs. It seems clear that using multiple belts and causing them to run as fast as possible and keeping the equipment under many atmospheres pressure, 10 mA is very unlikely to be exceeded.

The Van de Graaff machine is however one of the most useful for nuclear research due to the precision with which its potential can be adjusted and the following argument shows how the defects have been eliminated to produce a new type of high voltage generator capable of giving larger currents.

If a flow of gas is passed down an insulating tube and some of the gas molecules are ionized near the axis of the tube by some external means, the positive ions so formed will be carried along in the stream. Now, if an ion trap is introduced into the tube, the current may be collected and the trap raised to a high potential. Comparing this method of charging a terminal to a high +ve potential with the Van de Graaff several important differences may be stated.

(*i*) The charge is contained in a volume instead of being concentrated in a plane and hence there will be much weaker lateral fields and no tendency to breakdown unless very large currents are passed.

(*ii*) If momentary breakdown or any other form of ionization of the gas did occur there would be no drastic effect on the charging current since electrons, negative and positive ions all travel in the same direction, towards the collector.

(*iii*) Existing techniques, well established in wind tunnel design make it possible to use laminar flow gas as much as seven times as fast as belts.

(*iv*) The positive ions are not carried at the speed of the gas stream but have a backward drift equal to the mobility in the longitudinal field of the generator. For nitrogen at atmospheric pressure the mobility is 1·27 cm/sec/volt/cm and for a generator having the usual Van de Graaff gradient of 3 kV/cm this gives the ionic velocity as 3800 cm/sec. Gas velocities of several times this figure are readily obtainable and hence ions can be moved with considerable speed against such a field.

(*v*) The ions will not confine themselves to streamline motion but will diverge towards the walls of the tube by mutual repulsion. This is serious for the efficient transmission of ions down a long tube.

Suppose an attempt is made to design a one megavolt machine with a longitudinal gradient of 3 kV/cm and suppose the ions diverge in a cone of angle 90° then the length of tube is 333 cm and therefore the tube radius is 333 cm. The ionic velocity is 3800 cm/sec and the gas velocity will therefore be much greater than 3800 cm/sec, say 10,000 cm/sec. The required horse power to drive

such a tube is phenomenal—at least 1500 h.p. for closed return operation or 4500 h.p. for an open ended tube. Extra power would be required for the generation of electrical output and such a system would have to pass about one ampère to be reasonably efficient.

Experimental results obtained on the performance of corona discharge assemblies in air streams indicate that at this velocity it is only possible to take 20 μA from one point and it is most unlikely that anything approaching one milliamp would be obtainable from a machine of this size. The almost total loss of power due to aerodynamic drag would result in considerable heating of the gas and would necessitate the use of a very large refrigeration unit. It is apparent that such a system is quite pointless.

However consider a very small generator of the same type and let V be 30 kV, then L is 10 cm, r is 10 cm and u equals 10,000 cm/sec. Then the required power to overcome aerodynamic drag is only 4 h.p. of which most is expended in the fan and associated ducting and not in the 10 cm length of tube. It is possible to blow several such generators in series with almost no increase in power. All that remains is to fit corona discharge points to each collector so that each section may form ions on the axis of the next stage and the current may be carried from stage to stage indefinitely being alternately collected and discharged until the required potential is reached. Such a machine would have a similar current output to the previous example.

The actual arrangement designed to produce this effect is shown diagrammatically in *Figure 2*, and a single stage unit is shown in *Figures 1* and *3*.

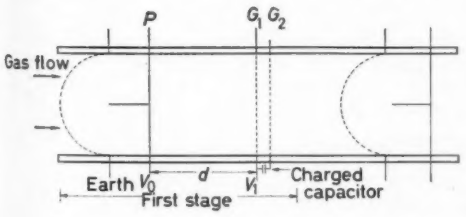

Figure 2. Experimental ionized gas flow high voltage generator

The Gas Flow Generator

A point is positioned at the centre of a hemispherical cage such that with the cage at earth potential the application of a suitable positive potential V_0 on the point causes a corona discharge. Positive ions recede from the point and would under static conditions be collected by the cage but with a moving gas stream as indicated; they are carried away towards the collector. The region between grids G_1 and G_2 is held at a sufficiently high field strength E_c such that the gas velocity

$$u < E_c \times U$$

where U is the mobility. The ions are therefore arrested and positive charge is collected by grid G_1 which is the output electrode of the first stage. When steady conditions are reached, with current being drawn from grid G_1 let the potential of this grid be V_1.

Considering the region between the point assembly P and grid G_1 the field strength is given by

$$E_T = \frac{V_1 - V_0}{d}$$

Where E is the field strength in the transit region between the discharge and the collector, and d is the length of this region. Hence for ion transmission

$$u > \left\{\frac{V_1 - V_0}{d}\right\} U$$

However if

$$u - \left\{\frac{V_1 - V_0}{d}\right\} U$$

is small the mutual repulsion of the ions becomes serious and the ions reach the tube walls before reaching the collector. This represents a loss of current but more serious is the very high potentials developed by the tube walls which can repel the entire ion stream back to the cage.

This was the difficulty encountered by M. MOREAU-HANOT[1] who with other workers turned her attention to the use of charged dust particles in air, the mobility of which is considerably less than that of gas molecules, while G. BABAT[2] investigated the use of mercury vapour ions for the same reason. The dust stream generator has been developed by M. MORAND, A. RASKIN and L. WINAND[3] up to 1 MV at one mA but ion current is lost to the tube walls resulting in inefficiency. In the apparatus being described here the emphasis is on efficient transmission of ions in clean gas with negligible wall collection.

Referring again to *Figure 2*, limiting V_1 it is possible to obtain 100 per cent ion collection. To the right is shown a second point and cage discharge system.

Let V_0 be 20 kV and V_1 be 80 kV—*i.e.*, voltage gain V_g is 60 kV—then connecting the output from the first stage to the second corona point and connecting the second cage to a source of potential of 60 kV the second system will discharge in a manner identical to the first and ions will again be

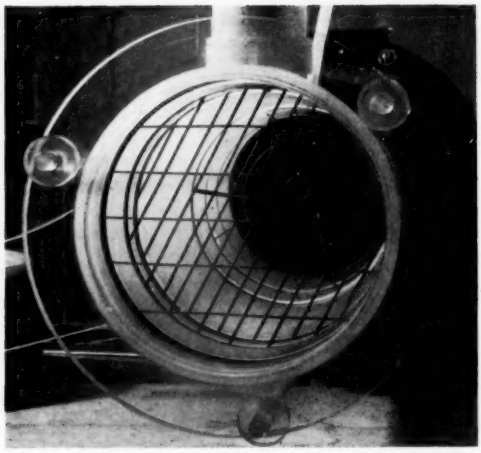

Figure 3. Generator tube viewed from the collector end. (Reproduced by courtesy of the Director of A.W.R.E., Aldermaston)

produced on the axis of the system, finally being collected and producing a potential

$$V_2 = V_0 + 2V_g$$

The 60 kV potential for the second stage may be tapped from a high value resistor chain between earth and grid G_1 of the first stage, no current being required. In the diagram the collector field E_c is shown held by a small condenser.

This system has worked well but would not be necessary in a multi-stage system when all collector voltages, except the last, would be tapped from a resistor chain. The final collector and output terminal would however require a built-in voltage supply to deliver about 20 kV. A two stage generator of this type has been tried at low speed and worked well.

Since every stage is identical and it has been found experimentally that it is possible to make ion transmission and collection 100 per cent, it follows directly that any number of stages may be added and the final terminal potential is limited only by insulation of the terminal collector. That is to say 6 MV is obtainable using standard pressurization as in the Van de Graaff. The layout of such a machine is shown in *Figure 4*.

Figure 5 indicates what current may be expected. The simple 15 cm tube of *Figure 2* has already given as much current as many medium sized Van de Graaff machines and there is every indication that at gas velocities of the order of 20,000 cm/sec very much larger currents are obtainable. In addition such apparatus is free from troublesome belt adjustment and deterioration, and due to the higher speed of the ions the electro-servo stabilization of the potential normally used on the Van de Graaff will have much faster response and result in steadier output.

Design of a High Powered Generator

It is not unreasonable to assume that an ion current of the order of one amp could be produced by a corona discharge, and that for a suitable size of tube this current could be efficiently passed from stage to stage. For a terminal potential of 6 MV this would mean that 6 MW of energy is extracted from the gas stream. Neglecting aerodynamic losses such a machine would require a blower motor of the order of 8000 h.p. This is in the field of quite orthodox medium size wind tunnel technique and could be driven by a gas turbine.

Too much speculation is futile at the present state of development but a high power machine has several interesting applications outside its use as a particle accelerator for nuclear research.

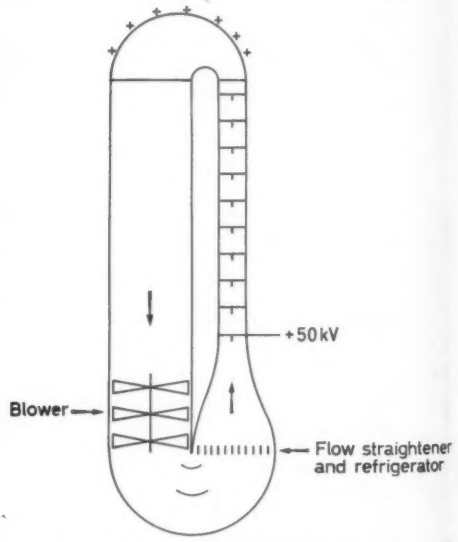

Figure 4. General layout of a gas flow generator—the discharge electrodes only are shown for clarity

Application of the Generator

Fission Reactors—By the acceleration of deuterons or protons to about one million volts it is possible to produce neutrons by reaction with suitable target materials. An ion current of one amp could be

expected to produce a neutron flux which over a small volume would be in excess of that existing in normal reactors. Not only would this arrangement rival the reactor in certain types of neutron physics experiments but it points the way to the design of a new type of reactor.

If a beam of neutrons is injected into a subcritical mass of fissile material some fission occurs and extra neutrons are produced. Should the mass be very nearly critical a chain reaction is initiated which although of finite length can cause the production of considerably more neutrons than were originally injected and resulting in the fission of many nuclei. It is only necessary to make the fissile mass as near critical as is possible with safety and inject a very large number of neutrons to make this system a power reactor in its own right. Such a device would be considerably lighter than the pile reactor and could be carried by an aircraft. Whether or not it would be possible to design an aircraft propulsion unit on these lines it is difficult to say at present.

Fusion Research—The normal method adopted for investigating the effect of temperature on gases is to charge up banks of condensers to a fairly high potential, say 50 kV, and discharge them via spark gaps through the gas. The only limit to the value of current obtained is the inductance in the circuit. Considerable effort has been expended on the design of low inductance capacitors but the difficulty of obtaining a sufficiently high rate of rise of current remains.

Consider the charged sphere of the high voltage generator as a source of power. Suppose the sphere to be two metres in diameter and to be contained in a pressure vessel of three metres diameter. The capacitance of the sphere will be approximately 0·0002 μF. At 6 MV the energy stored in the system is 36,000 joules and owing to the inherent low inductance of the arrangement a spark discharge to earth should give an extremely high peak current and could be passed through a step down pulse transformer to deliver extremely large current pulses at voltages suitable for fusion experiments. At an average charging current of one amp the repetition frequency would be 800 pulses per second compared with once every few seconds for most condenser charging units.

Radiography—The particular energy x-ray which will produce the radiograph containing the most information is very dependent upon the composition and thickness of the object being examined. However, even for thick dense material the energy required is never greater than six million volts since pair production causes serious absorption and scattering at energies as high as this and definition is lost. The Van de Graaff machine is therefore able to perform any radiograph, but due to its relatively low current and high cost this is not usually considered economic. Using the gas charging system however, with such a large current

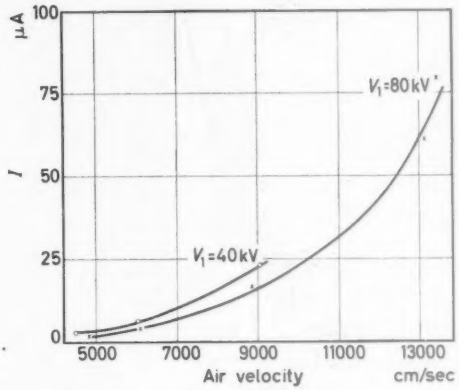

Figure 5. Performance of 15 cm diameter single stage ion tube

available one machine could perform a tremendous amount of work. At present positive charging only has been mentioned. This would necessitate having the electron target at the high potential end which is inconvenient, but not necessarily impracticable. Should this system prove to be of limited use one solution would be to draw pulses of power from the machine as indicated for fusion research and connect the x-ray tube to the secondary of the transformer.

In conclusion it may be said that all the techniques —high voltage, wind tunnel and compressor—have already been developed in other fields of technology, and that there does exist a requirement for a high current generator. The next step is a small one.

Acknowledgment must be made to Mr A. R. Howell of the National Gas Turbine Establishment, Pyestock, for permission to use the compressor, to Mr M. Cox for his assistance with the high speed measurements and to the United Kingdom Atomic Energy Authority for permission to publish this article.

The generating apparatus described is the subject of Patent Application No. 25966/59.

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SLIP CASTING METALS

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The process of slip casting metal powder is described and compared with ceramic practice. The physico-chemical relationships between powder and vehicle are discussed and the implications of the phenomena observed are related to the technology.

THE FABRICATION of complicated shapes from metals used in high temperature technology poses many problems. Difficulties due to refractoriness are, of course, to be expected, but in addition other properties may aggravate the problem. Consider for instance, such metals as tungsten, molybdenum, titanium and tantalum. All are refractory, but they are also readily oxidized and embrittled unless special precautions are taken during processing. Characteristics such as these make the normal metallurgical fabricating procedures of casting, forging and welding particularly difficult. In order to use such processes costly refinements of technique are required. Thus, any process that offers simplification in forming shapes is much to be desired.

Ceramic technology is extensively predicated on the use of materials that in massive form are both brittle and refractory. It is not unreasonable therefore, to investigate ceramic forming practice for a possible solution to the metallurgical problem just described. In general, the ceramic approach involves shaping operations with the material in powder form. The moulded green ware is consolidated by sintering to produce densification. Thus, certain adverse properties of the massive material are circumnavigated, and even turned to advantage in the manufacture of powders. For instance, the powder may be moulded by pressing or, where intricate shapes are required, treated as a paste or a slurry. Thus to a considerable degree, the rheology of the system may now be controlled by the physical and chemical relationships between the powder and the surrounding medium.

Extrusion of paste, jiggering, and slip casting are typical powder moulding processes used in ceramic technology. Extrusion is, of course, applied to the manufacture of elongated ware such as rods and tubes. Jiggering, a mechanized potter's wheel process, is used in making simple circular or oval shapes such as fireclay crucibles, dinner plates, cups and saucers. Slip casting is particularly useful when complicated shapes are required and is applied in the manufacture of objects ranging from delicate figurines to heavy sanitary ware. In view of the extensive use of slip casting in the ceramic industry, it is reasonable to consider its possibilities in the shaping of refractory metals. First, however, we will consider the nature of the process, and afterwards discuss the implications of its use in metal forming practice.

Ceramic Practice

Basically the process consists of pouring a stable* suspension of powder, called the slip, into an absorbent mould whose internal contours correspond to those of the outside of the object being formed. Excess vehicle, usually water, is abstracted by the porous mould until the casting is sufficiently hard to withstand the handling involved in withdrawal from the mould. Solid castings are made by continuously topping up the mould as the liquid subsides; hollow castings are similarly made, but surplus slip is drained after sufficient wall thickness has been built up against the mould walls. The simple equipment required is shown in *Figure 1* where the casting of a jet engine turbine bucket is illustrated. The various steps involved in this process are presented schematically in *Figure 2*. The low capital cost of the equipment used is particularly to be noted. For instance, no expensive large presses or dies are required.

A detailed discussion of the properties required of the slip has previously been presented elsewhere[1]. For present purposes attention will be confined to the most significant characteristics of the slip. In essence the central problem lies in making a stable slip that can be cast successfully to the required shape. Rheological control of the suspension is therefore of paramount importance.

Generally the densest slip possible, consistent with adequate fluidity, is required in order to minimize subsequent removal of water by the mould. Thus, a critical point in the process is to provide the correct conditions for maximum mobility of particles in the minimum quantity of water.

In order to make stable suspensions it is common practice in ceramic technology to use particles most

* The term 'stable' is here taken to mean that the suspended powder does not settle appreciably during the time it takes to make a casting.

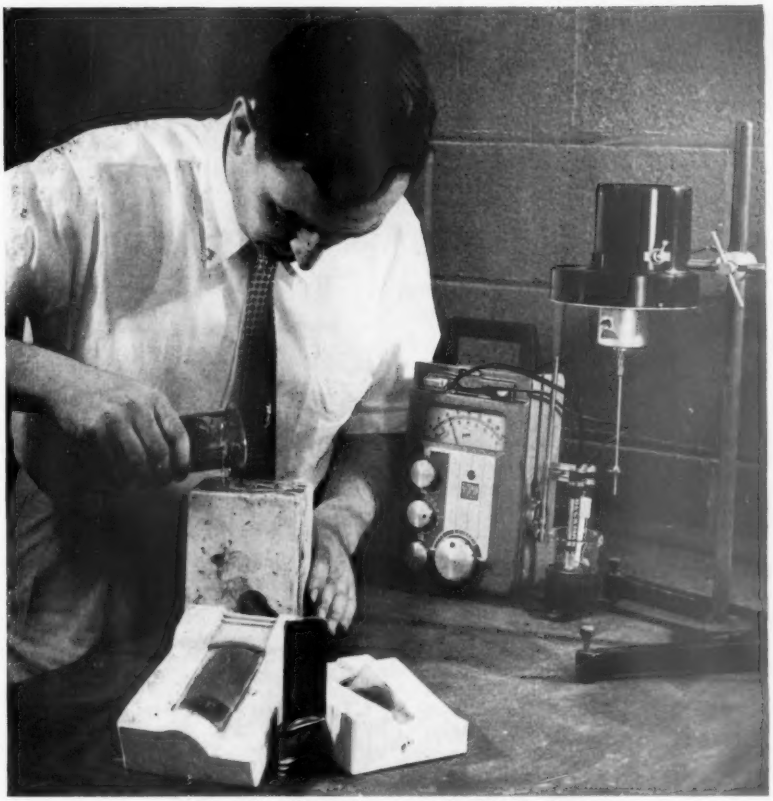

Figure 1. Slip casting a metal turbine bucket

of whose diameters lie in the 0 to 10 microns range. These powders are much finer than the final 325 mesh screen (44 microns opening) commonly used in sieve analysis. Although physical factors, such as particle size distribution and solid/liquid ratio, significantly influence the fluidity of the system, rheological control is dominantly a chemical consideration. It is important to appreciate this point fully. The addition of powder to an ionic liquid is not a simple physical process. In such a medium particles acquire electric charges on their surfaces through the adsorption of ions. An electrical double layer, as described by Helmholtz and later Gouy and Stern, is built up around each particle. Thus the rheology of the system is an expression of the interaction of the electrical charges.

Rheological changes are made by modifying the double layer. The nature and degree of variation to be expected has been extensively discussed by E. J. W. VERWEY and J. T. G. OVERBEEK[2]. For the present discussion, however, it is only necessary to note the tremendously potent effect of electrolyte addition on slip viscosity. Since water is the only vehicle of economic importance, attention will be confined to the phenomena observed on adding powder to aqueous media. Consider, for instance, the effect of hydrion concentration on the viscosity of a thoria slip. *Figure 3* clearly shows that for a given slip density minimum viscosity is attained at approximately pH 4. Viscosity changes rapidly about the minimum. Thus a small change in ionic atmosphere can change the fluidity of a slip from that characteristic of, say, glycerine to a paste resembling cement.

Metal Practice: Rheology

It is pertinent to inquire whether the same sort of rheological behaviour may be anticipated in the case of aqueous metal slips. An analysis of the problem may be made by considering the differences

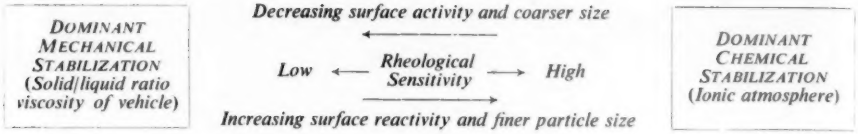
DOMINANT MECHANICAL STABILIZATION (Solid/liquid ratio viscosity of vehicle)
Decreasing surface activity and coarser size
Low
Rheological Sensitivity
High
Increasing surface reactivity and finer particle size
DOMINANT CHEMICAL STABILIZATION (Ionic atmosphere)

Figure 2. Steps in fabrication of objects by slip casting

between metal and ceramic surfaces. It has been stressed that the rheology of ceramic suspensions is substantially dictated by the interaction of the surface charges on the particles. Thus the problem resolves itself into a question of whether or not metals will similarly acquire such charges.

It seems most unlikely that a pure metal surface will support an electrical charge similar to that detected on ceramics. Most metals, however, have an oxide coating on their surfaces. If the oxide surface is preserved, the water or vehicle actually sees a ceramic, and the system behaves accordingly. *Figure 4* shows the pH–viscosity relationship for a molybdenum metal slip[3].

The fluidity of the molybdenum slip is greatly increased by adjusting the acidity to pH 6 to 7. Restated and placing the emphasis differently, the

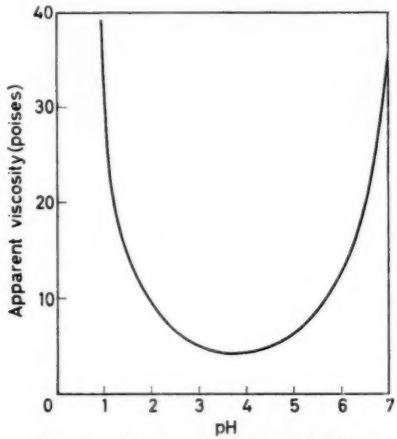

Figure 3. pH–viscosity relationship for an aqueous thoria slip

densest slip for a predetermined viscosity may be obtained in this pH range. H. H. HAUSNER *et al.*[4] have shown that a similar relationship exists for stainless steel and water. In this case, however, the viscosity minimum is at approximately pH 10·5. It is presumed that the presence of a chromium sesquioxide (Cr_2O_3) surface causes the effect observed.The relationship between the pH–viscosity curves for metals and their oxides is discussed in more detail elsewhere[5].

The rheology of the metal suspension may change with time and the rate of change is a function of the fineness of the particles present. Unlike a ceramic the oxide surface on a metal is not necessarily dense, and under certain ionic conditions dissolves readily. It may be anticipated that this will bring about changes for at least two reasons. A metallic surface is now exposed to the vehicle, and in addition solution of metal oxide itself contributes to the ionic atmosphere surrounding the particle. For instance, metals of high valency such as molybdenum are likely to have considerable coagulating power according to the Schulze–Hardy rule. Thus removal of the oxide film by solution changes the condition of stability, since both particle surface and ionic atmosphere are changed.

The viscosity relationships of metal powder slips are further complicated by the particle sizes commonly encountered in powder metal practice. Although a metal particle may acquire a charged double layer in the manner described, the interactions caused by its presence will only be detected rheologically when the forces involved are of similar or of greater magnitude than those of gravity or the convection currents in the vehicle. Hence the rheology of coarse metal powder (greater than 10μ) slips is dictated by physical factors such as hindered settling, *etc.* If, however, the same metal is ground into fine powder it will form slips whose rheological properties depend greatly on the nature and extent of the ionic species in the water vehicle.

Clearly, the mode of making a stable suspension will depend on the size and nature of the metal particles involved. Thus, in making a slip with an inert metal powder, or equally with coarse particles (greater than 10μ) of an active metal rheological control will be effected largely through variations of the solid/liquid ratio, and viscosity of the vehicle. Since water is the vehicle of most commercial interest means must be devised for controlling its viscosity simply and cheaply. Fortunately this can be done by the addition of small amounts of organic

gelling agents such as alginates. For instance, as little as two per cent of one brand of ammonium alginate raises the viscosity of water from one centipoise to 30,000 centipoise.

In the case of a slip made with a fine powder of a surface active metal the considerations just discussed will still be operative, but in addition the rheology may be determined by the numbers and identity of ions in the vehicle surrounding the particles. This has been demonstrated in *Figure 4* where a change in pH from 7 to 8 doubles the apparent viscosity. The relative importance of these physical and chemical factors varies with slip dilution, particle size distribution and surface chemical activity of the metal powder. By using more vehicle, or coarser particles, in a given slip the steepness of the curves is diminished. In either event a thinner slip is produced. In practice a proper balance must be struck between the various conflicting requirements.

The relationship between slips is illustrated in *Figure 5*. Physical control is less sensitive than chemical, as shown by comparison of the data given in *Figures 4* and *6*. Note that for molybdenum slips a considerable increase in liquid is required in order to reduce viscosity substantially.

It would be instructive at this point to compare specifically two slips whose rheological characteristics are controlled by the two different means. At present the literature only contains detailed information on two such slips, *viz.* molybdenum[3] and stainless steel[4]. The essential data for molybdenum have already been discussed in previous sections. The work of HAUSNER *et al.*, on stainless steel powder is interesting, because it illustrates an intermediate case where both chemical and physical controls were used to obtain the desired slip. The oxide coating (Cr_2O_3) on stainless steel renders the slip amenable to chemical control[5]. Commercial powder, however, is relatively coarse and would not be sensitive to such a method of treatment. By screening and reblending into two particle size fractions a slip was produced that had the pH–viscosity characteristics shown in *Figure 7*. It will be observed on comparison with the molybdenum slip that the viscosity was less sensitive to pH change. The slip, however, was much more viscous throughout the pH range studied, even though the liquid to solid ratio was high. In order to prevent the coarse fraction settling rapidly a viscous slip was necessary and was obtained by the use of alginate additions. In spite of the greater dilution and high viscosity satisfactory dense castings were produced, the properties of which will be discussed later.

Besides the flow properties characterized by the viscosity coefficient, metal slips also exhibit other rheological phenomena. Dilatancy and thixotropy are frequently observed characteristics of many ceramic slips, and it is not surprising therefore to detect them in metal powder suspensions. A dilatant slip resists pouring and hardens when

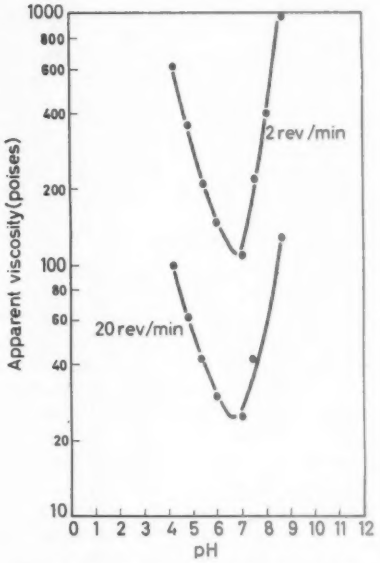

Figure 4. pH–viscosity relations for a fine molybdenum powder suspended in 5 per cent aqueous polyvinyl alcohol solution. 1·15 volumes liquid: 1 volume solid. Viscosity measured with a Brookfield viscometer

disturbed. Such slips, on pouring, have the appearance of miniature ice fields that are breaking up into ice rafts. Needless to say suspensions of this type are most undesirable, since they do not pour well, nor do they properly fill the fine detail in the mould. The phenomenon seems to be associated with dense, well deflocculated, fine powder suspensions. Although these latter conditions are generally desirable it must be recognized that when stressed the particles may move to form a more open structure. As a consequence of this regions deficient in lubricating liquid appear throughout the suspension. The condition is usually rectified by diluting the slip until it is insensitive to the stresses normally incurred during processing.

Superficially at least, thixotropy may be regarded as the opposite phenomenon to dilatancy. There is much discussion among rheologists on the exact phenomena to be covered by this term[8,9]. Ceramicists, however, use it to imply softening or

easier flow when a paste or suspension is stressed. In slip casting a minor expression of this property is even desirable. Such slips pour well, drain cleanly, and produce castings that part readily from the mould on slight jarring.

Thixotropic properties in pastes are utilized in making castings of thick section ware such as glass tank blocks. Normal slips would not cast properly in such applications. The casting parts from the mould long before the bulk of vehicle has diffused out and a wet inhomogeneous product is obtained. By making a thixotropic paste that can be poured when vibrated but sets when at rest a dense uniform dry casting can be made. The author has applied this technique to making molybdenum discs.

Metal Practice: Casting

It is important to be able to predict the type of slip that will result from mixing a given powder with a particular vehicle. Such knowledge leads not only to the means of devising rheological control, but also indicates the type of absorbent mould that should be used in casting. For instance, slips controlled by chemical means typically form castings that readily part from the mould on initial drying. Such castings are desirable, because they are easily removed from the mould.

The following explanation is offered to account for this shrinkage. Chemically controlled slips are cast in a deflocculated condition, since this optimizes the density–fluidity relationship. Under such conditions fluid slip can frequently be made with a solid content in excess of 50 volume per cent. In the vicinity of the mould wall, however, the slip undergoes a considerable rheological change due to removal of vehicle. The change in solid/liquid ratio causes the formation of a semi-stiff casting that reproduces the contours of the mould. Since the particles repel one another through their superficial electrical charges, the resulting freedom of movement permits fairly dense packing. The minimal settling volume of deflocculated particles is a phenomenon well documented in the field of colloidal chemistry.

The well packed particles greatly impede the passage of vehicle to the porous mould. Also the presence of a tightly adhering water film around each particle, held by dipole attraction, probably plays a role in diminishing vehicle diffusion rates. As the wall of the casting thickens diffusion of vehicle continuously diminishes. When appreciable transfer of liquid ceases the casting suddenly parts from the mould wall. This is due to the surface tension forces of the remaining vehicle pulling the particles together to form an object of smaller surface area. Although the particles are already fairly well packed the presence of water films permits them to accommodate to the new conditions in the system. In short, the particles are adequately lubricated and move under the surface tension forces.

It is suggested that this hypothesis may also explain why thixotropic bodies part so readily from the mould on jarring. The stress transiently induced in the body causes it to become soft for a short while. During this period the surface tension forces in the vehicle draw the particles together and being free they move to equilibrium positions. Prolonged or continued vibration is undesirable since it causes the casting to slump and eventually form a shape of minimal surface area.

Slips made from coarse or inert powder are not so readily released from the mould. In the light of the preceding discussion this is to be expected. Such slips are necessarily quite dilute, since the particles are agglomerated and require relatively large quantities of vehicle to separate the flocs. The system has no deflocculating properties, and hence the particles are drawn to the mould walls where they agglomerate further to form a very open structure through which the vehicle readily passes. The slip casts rapidly, and the casting formed is much drier than in the previous case. Surface tension forces can no longer promote a rearrangement of particles to a smaller volume, since a bridge structure already exists. In addition the size of the capillaries is larger and the number present smaller than for deflocculated slip, hence the surface tension forces are weaker.

It is thus possible to anticipate the severity of the mould sticking problem and take proper steps to

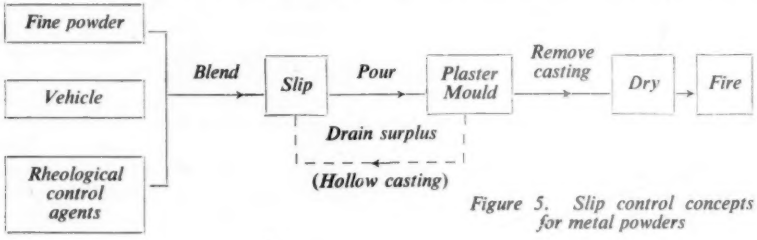

Figure 5. Slip control concepts for metal powders

overcome it. In ceramic practice plaster moulds are invariably used. Slips are of the chemically controlled type, and when difficulties are encountered they are overcome by suitably adjusting the slip. The necessary modification may involve changing the electrolyte additions, or altering the particle size distribution of the powder by varying the grinding schedule. It has already been indicated that coarse powders are not so amenable to rheological control by chemicals even when the particles support an electrical charge. Equally, however, excessively fine powder (very much less than 1μ) is unduly sensitive to chemical change. Castings of such materials shrink considerably and crack on parting from the mould.

In slip casting metals there are many occasions when the usual means of bringing about mould release cannot be applied. For instance, further grinding might be economically undesirable and the increased probability of oxygen pickup might also be reflected in the properties of the final fired ware. Under these circumstances it may be found that a stable slip can be made by proper use of the physical controls previously described but difficulty is experienced in withdrawing the casting from the mould. Since the slip cannot be modified further, the situation can be rectified only by changes in the mould.

There are at least two general solutions to this problem. The most obvious is to line the mould cavity with some strippable medium such as paper. Filter paper has frequently been used with success, but its application is limited to situations where the geometry of the mould is relatively simple. P. E. REMPES *et al.*[6] have described a method in which the mould is coated with a thin film of ammonium alginate. This compound when suitably applied forms a permeable membrane with a texture like fine tissue paper.

Another approach to the problem is to make the mould expendable. For instance, castings may be made by pouring slip into a rammed mould of Albany sand[3]. An even better method, however, is to cast into a preformed absorbent paper mould. The paper may be burned off during the sintering operation. This latter technique has much to recommend it as a general production method, quite apart from it being a solution to a specific problem. Even under the best circumstances stripping a plaster mould calls for skill, and is in addition a relatively slow operation. The preparation and use of plaster moulds also calls for skilled labour that is not readily obtained. For quantity production it should not be difficult to contract with a paper company to manufacture moulds of the type described. One of the disadvantages of slip casting, low production rate, would also be minimized by the use of expendable paper moulds. An inventory of paper moulds would also be much cheaper and smaller in volume than the equivalent in normal plaster moulds.

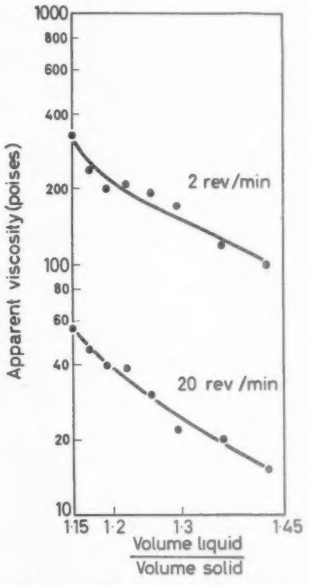

Figure 6. Effect of dilution on the viscosity of molybdenum slip (pH 7·7 throughout experiment); viscosity measured with a Brookfield viscometer

Metal Practice: Drying and Firing

Drying and firing call for little special comment. Metal powder castings are subject to problems similar to those encountered in ceramic ware. The greater thermal conductivity of metals, however, permits faster drying rates with less danger of cracking than is possible for ceramics. The turbine bucket shown in *Figure 1* for instance may be plunged into a furnace at 1800°C after overnight air drying and ten minutes warming on the forehearth of the furnace.

Heavy ware with thick sections may present a problem when cast from a heavily doped slip. Film forming organics such as polyvinyl alcohol used to improve slip stability and green strength in cast ware impede the evaporation of vehicle. The skin formed on the surface shrinks as it dries, and thereby initiates a crack. The crack is propagated by the continued drying and shrinking of the outer layers

of the casting. This problem may be overcome in several ways. Drying under controlled humidity conditions is probably the most desirable method, but transferring the point of skin formation to an expendable medium can also be effective. Thus burying the ware in damp powder lessens cracking

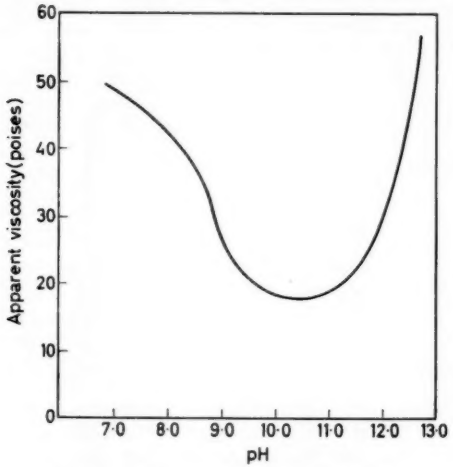

Figure 7. pH–viscosity characteristics for a 317 type stainless steel slip[4]*. Powder contains 20w/o —100+150 mesh spherical particles; 80 w/o —325 mesh spherical particles, two per cent ammonium alginate solution (from* HAUSNER *et al.*[4]*)*

tendencies due to skin formation. In the case of molybdenum castings made from polyvinyl alcohol bearing slips it was noted that firing before the ware was completely dried was desirable. Presumably the skin chars under these circumstances and permits the free passage of water.

Metal Practice: Properties

Having utilized a new method for moulding metal powders it is interesting to consider its effect on the consolidated product. We may reasonably inquire whether slip cast powder compacts are different from those made by pressing. At present insufficient data are published to make a definitive statement. So far as density is concerned slip cast ware sinters to similar final densities as pressed compacts. In the domain of mechanical properties H. H. HAUSNER[7] reports that some slip cast stainless steel specimens are stronger and more ductile than equivalent pressed samples. He quotes as an example a 316 stainless steel bar sintered at 1350°C to 98·5 per cent of theoretical density having a tensile strength of 77,500 p.s.i. with an elongation of 56·6 per cent. These figures approach those quoted for wrought and annealed stock. Hausner has suggested that the improvement in mechanical properties over pressed compacts is related to the absence of cold work in the slip cast ware. It is not easy to appreciate wherein this condition can have any substantial bearing on the strength properties of sintered ware. The amount of cold work caused by pressing powder is probably very small and in any event is quickly annealed out during sintering.

No special properties were observed in the case of slip cast molybdenum. Material with equivalent structure had similar mechanical properties to molybdenum made by pressing.

Conclusion

It has been indicated that slip casting is an attractive means of shaping metals that are normally difficult to work or cast. This statement, however, is not intended to be confining in any way. For instance, the powder metallurgy group at Stevens Institute (Hoboken, New Jersey) has made large castings (45 lb) from copper powder and other malleable materials. Slip casting offers interesting possibilities in alloying, both in the achievement of homogeneity and, where required, in the manufacture of layered composites. Thus, under certain circumstances, slip casting may be applied competitively against traditional methods even though moulding is not a critical factor in processing. The analysis presented in this paper indicates that if the process is properly understood its technical limitations are likely to be less severe than the economic factors involved.

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GAS CENTRIFUGES

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After discussing the theoretical basis of the centrifugal method, especially thermally controlled countercurrent gas centrifuges, the types of centrifuges used in Germany and by German scientists in Russia are described. Enrichment experiments with three different centrifuge models gave the static enrichments, the dependence of the enrichment on the throughput, and the separation potential of the centrifuges. Experimental separation potentials allow a comparison of the gas centrifuge method with the gas diffusion method for the enrichment of the uranium isotopes.

THE IDEA of using centrifugal fields to separate gaseous mixtures of different molecular weights is old; BREDIG[1] carried out experiments of this kind as early as 1895, and, soon after the discovery of the isotopy of the elements, LINDEMANN and ASTON[2] suggested the use of this method to increase the concentration of isotopes in gaseous form. The experiments were, however, unsuccessful until BEAMS and his collaborators[3] were able to develop gas centrifuges which could run in a high vacuum, free from vibrations, and which were so well insulated thermally that undesirable convection of gases within the rotor was prevented.

The theory of the gas centrifuge is based on the pressure distribution of a gas in a gravitational field, as given by the barometric formula. From this, the distribution of concentration of a mixture of two isotopes having masses M_1 and M_2 and molar fractions N and $1-N$ in the centrifugal field of a rotor with radius r_2 and angular velocity ω works out to be:

$$[N/(1-N)]_{r_2} = [N/(1-N)]_{r_0} \times \exp(M_1 - M_2)\,\omega^2 r_2^2/2\,RT \quad \ldots (1)$$

where R is the universal gas constant and T the absolute temperature.

The equilibrium separation factor for a single process is

$$\alpha_0 = \exp(M_1 - M_2)\,\omega^2 r_2^2/2\,RT \quad \ldots (2)$$

which can be replaced by

$$\alpha_0 = 1 + (M_1 - M_2)\,\omega^2 r_2^2/2\,RT$$

at the peripheral velocities attainable. It depends only on the difference of the masses, and not, as in most other separation methods, on the relative mass. This makes the centrifugal method particularly suitable for isotope enrichment of heavy elements, which can be incorporated in molecules as heavy as convenient.

Isotope Enrichment by Centrifuge

For the uranium isotopes U^{238} and U^{235} for a peripheral velocity of 300m/sec $\alpha_0 - 1$ equals 0·0549, and for $\omega r_2 = 400$m/sec it equals 0·0976, so that the enrichment amounts to 5·5 per cent and 9·8 per cent respectively, while in the gas diffusion method $\alpha_0 - 1$ is only about 0·004, that is, an enrichment of 0·4 per cent.

These enrichment values are obtained in a simple follow-through centrifuge in which the starting mixture is put in at one end of the rotor, while at the same time the fraction enriched in the lighter component is tapped off at the other end at the axis, and the fraction enriched in the heavier component at the edge.

Since the separation factor for a single process which can be achieved in a gas centrifuge is very much greater than in the gas diffusion method, methods were soon developed to increase the degree of enrichment inside a centrifuge. One which may be mentioned is MULLIKEN's evaporating centrifuge[4], in which the mixture of isotopes to be separated lies at the wall of the rotor as a liquid film, while vapour enriched in the light isotope is tapped off at the axis, so that the enrichment of the heavy isotope in the remaining liquid is multiplied; in HARTECK's oscillation centrifuge[5] the single separating stage is multiplied by an oscillation flow of the isotope mixture through suitably arranged chambers inside the rotor.

Countercurrent Centrifuge

The most successful method has been found to be the countercurrent centrifuge, of which the theory was given as early as 1938 by MARTIN and KUHN[6] for the case in which it is thermally controlled. The theory of the gas centrifuge was developed during the war, and put into general form by COHEN[7].

BEAMS and his collaborators[3] in the U.S.A., and GROTH and his collaborators[8] in Germany, were able at the same time to show that the gas centrifuge method can be used successfully for increasing the concentration of uranium isotopes, and that there is good agreement between theory and experiment. Thermally-controlled countercurrent centrifuges have been developed in Germany in the last few years by BEYERLE, GROTH and their collaborators[9]. It is now known that a group of German scientists under STEENBECK[10] working in the U.S.S.R. since the end of the war developed a countercurrent centrifuge based on a different principle.

Separation Potential

In order to deduce the partial differential equation for centrifugal separation which may be applied to all types of gas centrifuges, all the currents of gas

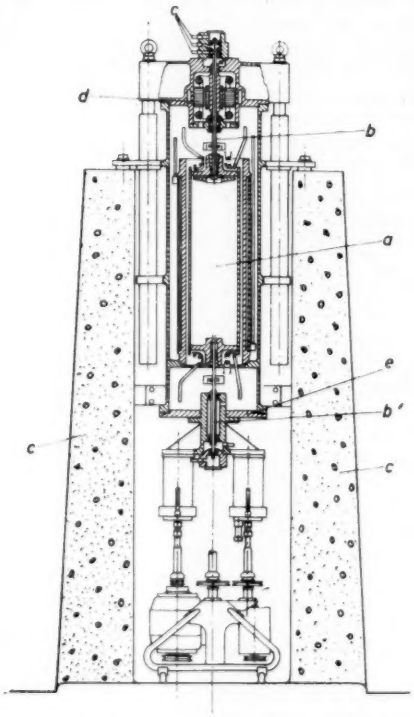

Figure 1. Vertical section through centrifuges ZG 3 and ZG 5 (diagrammatic) (GROTH, W. *Courtesy Chem.-Ing.-Tech.* (1959) **5** 310)

inside the rotor are considered: the ordinary diffusion current, striving to balance the concentration gradient along the radial direction; pressure diffusion, which strives to produce the barometric distribution; the radial and axial convection currents, which, by means of suitable devices, are imposed on the gas in order to intensify the separation; and back-diffusion in the axial direction.

Figure 2. Gas centrifuge ZG 3. (GROTH, W. *Courtesy Chem.-Ing.-Tech.* (1959) **5** 310)

With the aid of this equation the separation potential of a gas centrifuge may be given in a general form. The concept of separation potential was introduced by UREY[11] into the theory of isotope separation. It gives the value of a quantity of separated material, that is, it is proportional to the number of separation elements required to produce this quantity. The separation potential equals the product of the molar quantity produced per second and a function which depends on the molar fractions of the initial and final concentrations. The function equals 1, for example, for a cascade which in the enrichment section increases the concentration of U^{235} from its natural value up to 1·65 per cent, and in the stripper section reduces the natural concentration of U^{235} by half.

With the aid of the separation potential, BECKER[12] defined specific investment factors, the 'specific electric investment' and the 'specific investment cost', which represent characteristic factors of the separating process which can be calculated from the optimum operating data of the separation element, and make it possible to compare the efficiency of various separating methods.

The maximum separation potential of a gas centrifuge is:

$$(\delta U)_{max} = \frac{D.p}{RT}\left[\frac{\Delta M\ \omega^2 r_2^2}{2RT}\right]^2 \frac{\pi L}{2} \quad \text{mole/sec}$$

$$= \rho D\left[\frac{\Delta M\ \omega^2 r_2^2}{2\,RT}\right]^2 \frac{\pi L}{2} \text{ g/sec} \ldots (3)$$

where D = diffusion coefficient, p = pressure, ρ = density of the gas, L = length of centrifuge rotor. $(\delta U)_{max}$ is proportional to the 4th power of the peripheral speed ωr_2 and to the length L of the rotor of the centrifuge. If the peripheral speed is constant, it is independent of the radius.

The peripheral speed is limited by the tensile strength of the rotor material, which is thus of fundamental importance in the centrifuge process; the ratio of tensile strength to density must be greater than $(\omega r_2)^2$.

In countercurrent centrifuges the separation factor of a single process (in the direction of the radius) is multiplied many times, producing an axial countercurrent, which takes place along the axis in one direction and along the walls of the rotor in the opposite direction. A concentration gradient is formed in the direction of the axial countercurrent, and its value is limited only by backdiffusion. These have great advantages over centrifuges, *viz*: Since a high separation factor can be attained in a single unit, much of the transport of gas between units, which is required in other methods, may be avoided, and the construction of a cascade is very much simplified: and since the number of stages required to achieve a given enrichment is very much reduced the cascade may be made broad instead of long, and can thus be easily sub-divided into parallel sections independent of each other. The countercurrent centrifuge is moreover particularly good because it can be operated with maximum separation potential throughout the whole unit.

The maximum value of the ratio of the molar fractions at the ends of the rotor, calculated from the differential equation of the countercurrent centrifuge, is:

$$\frac{N(L)}{N(o)} = \exp\left\{\frac{\frac{\Delta M\ \omega^2 r_2^2}{2\,RT}\cdot\frac{2}{r_2^2}\int_0^{r_2} r\,dr\int_0^r p\,\omega\,r\,dr}{r_2\sqrt{\left[2\int_0^{r_2}\frac{dr}{r}\left(\int_0^r p\,\omega\,r\,dr\right)^2\right]}}\right\} L \ldots (4)$$

where ωr_2 = velocity, $\int_0^r p\,\omega\,r\,dr$ = current density of axial convection current.

The separation potential of the countercurrent centrifuge is given by

$$\delta U = \left\{\frac{\left(\frac{\Delta M\ \omega^2 r_2^2}{2\,RT}\right)^2\left(\frac{2}{r_2^2}\int_0^{r_2} r\,dr\int_0^r p\,\omega\,r\,dr\right)^2}{\int_0^{r_2}\frac{dr}{r}\left(\int_0^r p\,\omega\,r\,dr\right)^2}\right\} \times \left(\frac{\pi L}{2}\right)\left(\frac{m^2}{1+m^2}\right) \text{ mole/sec} \ldots (5)$$

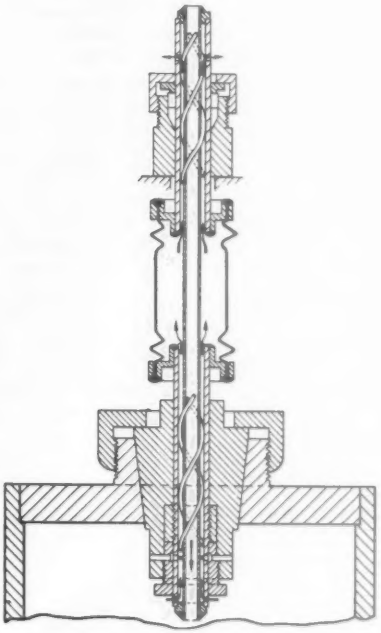

Figure 3. Section through tubular shaft (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

Figure 4. Tubular shafts (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

m is a measure of the total convection flow, $(\delta U)_{max}$ occurs when $m \to \infty$, but when $m = 3$ it is already 90 per cent, and when $m = 5$ it is 96 per cent, of its maximum value. It is therefore possible to reach high values of δU without reducing the enrichment sharply, and without making the convection currents extremely large.

Flow Profile

The flow profile of thermally-controlled gas centrifuges, in which the countercurrent convection is produced by keeping one rotor cover at a higher temperature, and the other at a lower temperature, than that of the gas, cannot be given exactly, but MARTIN's calculations[13] of the radial flow of a gas in a strong centrifugal field between two surfaces at different temperatures make it possible to estimate the flow in the axial direction. According to Martin's flow profile the cylindrical neutral surface, which separates the upward from the downward current, lies near the wall of the rotor, and the heavier the gas mixture to be separated the nearer it lies. The consequence of this is that a better approximation to the maximum value of the separation potential for optimum flow profile is obtained the heavier the gas used. This fact was confirmed experimentally in tests with argon, xenon and uranium hexafluoride; it follows from it that the gas centrifuge method is particularly suitable for increasing the concentration of isotopes of heavy elements.

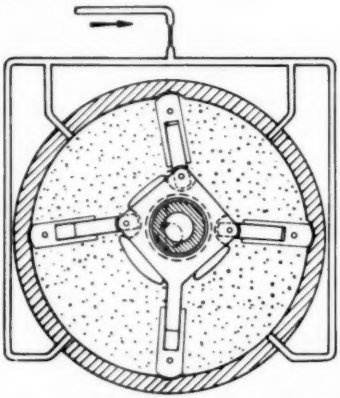

Figure 5. Section through chamber damper bearing (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

Thermally Controlled Gas Centrifuges

The two types of centrifuge[8] used in Germany are built on the principles given by BEAMS[3]: the cylindrical rotor a is suspended with vertical axis

Figure 6. View of chamber damper bearing (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

of rotation from a highly-elastic double-walled tubular shaft b, which serves for entry and exit of the gases, and is connected to the driving motor. At its lower end there is a second tubular shaft b', which also serves to remove the gas. *Figure 1* shows schematically a vertical section through a centrifuge of type *ZG 3* and *ZG 5*. The cylindrical casing, which is filled with hydrogen at a pressure of a few mms Hg, rests on two concrete pillars c. It contains the safety jacket, supported so that it can be rotated, which is double-walled and connected to a thermostat. The upper end of the casing is closed by the motor unit d, which also supports the upper gas tightening. The lower end of the case is closed by a cover e with a central extension for the lower bearing of the tubular shaft, and carries the gas-tight sealing for the bottom. This type is fitted either with a rotor of 66·5 cm internal length, or with a longer rotor of 113·0 cm internal length; the internal diameter is 18·5 cm in both cases, and the internal peripheral velocity 302 m/sec. *Figure 2* shows a centrifuge of the type *ZG 3*.

The dimensions of the rotors which have been used are given in *Table 1*.

The rotors were made of tubes of *Bondur*, an aluminium alloy. Since the ratio of tensile strength to density determines the permissible peripheral velocity, titanium alloys would be even more efficient, enabling peripheral velocities of more than 400 m/sec to be attained.

An increase in the radius certainly reduces the ratio $L/2r_2$, and thereby the degree of enrichment which can be achieved in the centrifuge, but does not reduce the determining factor, which is the separation potential. On the other hand, to have a

Table 1. Dimensions of rotors

Type	*L (cm)*	r_2 *(cm)*	$L/2r_2$	*rev/min*		
				302m/sec	*340m/sec*	*400m/sec*
UZ I	40·0	6·0	3·33	47,800		
UZ IIIB	63·5	6·7	4·74	42,800		
ZG 3	66·5	9·25	3·60	31,000		
ZG 5	113·0	9·25	6·11	31,000		
ZG 6	240·0	20·0	6·0	14,340	16,145	18,300
ZG 7	316·0	22·5	7·02	12,750	14,350	16,890

bigger radius for the rotor has this advantage from the mechanical engineering aspect, that the same peripheral velocities can be obtained with lower angular velocities. In this way the diameter of the tubular shafts and of the bearings can be increased without increasing the friction at the bearings.

It is necessary to have a large diameter for the tubular shafts in order to enable enough gas to flow through. On the other hand, the tubular shafts must be very elastic, so as not to transfer any vibrations produced by unbalance of the rotor to the parts of the shaft which the casing supports, thus preventing any increase in wear on the bearings and any vibration on the shaft occurring in the gas-tight seals, which are labyrinth seals. To fulfil both these requirements, the construction shown in *Figure 3* was developed. The weight of the rotor is supported by a thin-walled tube or rod, while the tubular shaft consists of two parts, connected by means of a thin-walled, highly elastic metal bellows. *Figure 4* gives a view of the tubular shaft.

Very important, from the constructional point of view, are the damper-bearings, which are situated above and below the rotor. These bearings should offer sufficient resistance to the precession of the rotor axis without counteracting vibrations of the rotor resulting from unavoidable unbalances. To fulfil both requirements, the damper bearing shown schematically in *Figure 5* was developed. It consists of four oil chambers, separated by telescopic links, containing oil under high pressure. Any precession of the rotor axis is damped by the resulting passage of oil from one chamber to another. *Figure 6* gives a view of the damper bearing.

For gas convection inside the rotor, the heat of compression produced by the radial flow at one end must be removed by the cover, which is cooled by an annular cooling chamber, and the heat of expansion must be supplied by the other cover (*Figure 7*). For this purpose it is heated by eddy currents induced either by an electromagnet or by a permanent magnet. Non-rotating metal rings in a ring-shaped boring are used to measure the temperature. As they are only a short distance from the cover, and as the casing is filled with hydrogen, they are at practically the same temperature as the cover. Their temperature is measured by means of temperature-sensitive semiconductor elements.

Oil seals with fluorinated oils, of a type specially constructed for the purpose, seal off the inside of the rotor from the outside at the bearings. Concentric with the rotating tubular shafts a non-rotating

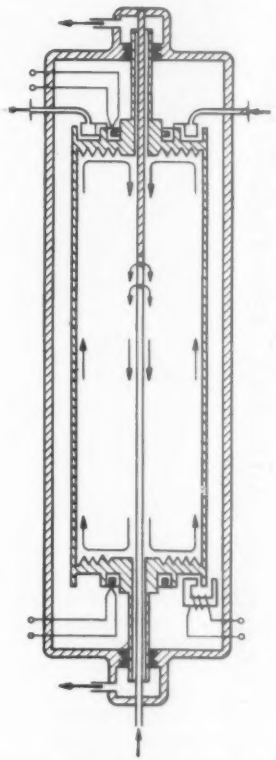

Figure 7. Temperature-regulating device for centrifuge ZG 3 (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[11] (1959) **19** 1)

shaft is extended, passing through the whole rotor, through which the gas is introduced at a height (in the rotor) which corresponds to its initial concentration; it also serves to measure the pressure of the gas at the axis. This tube is prevented from vibrating by suitable damping devices.

The rotor of the centrifuge, which also consists of aluminium alloy, has a thin wall (about 1 mm thick) and is supported on a thin flexible needle, rotating in a deepening in a metal plate. The plate is elastically centred and oil-damped. This type of support makes the system self-stabilizing. At the upper end

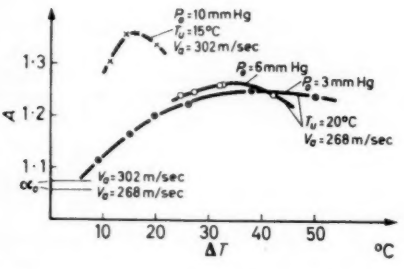

Figure 8. Relation between enrichment, A, and pressure, peripheral speed and mean temperature (argon) ($G = O$) (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

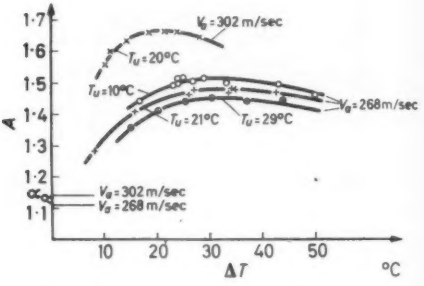

Figure 9. Relation between enrichment, A, and pressure, peripheral speed and mean temperature (xenon) ($G = O$) (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

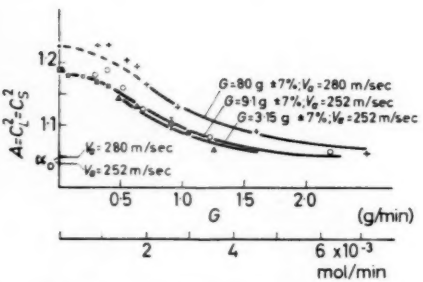

Figure 10. Relation between enrichment, A, and throughout, G, (UF_6) (BEYERLE, K. *and* GROTH, W.[14]; *courtesy North Holland Publishing Co.*)

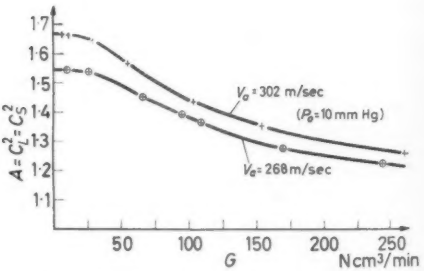

Figure 11. Relation between enrichment, A, and throughput, G (xenon), ($G_o = G_u = G/2$, (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

The light and heavy fractions are led out from the ends of the rotor. At the exit points the gas pressure is raised by means of Pitot tube conveyors placed in end chambers, whose lids (facing the inside of the rotor) are provided with holes, and which prevent the decrease in the speed of rotation of the gas, caused by friction, from spreading to the inside of the rotor. This eliminates the need for pumps to transport the gas between the stages of a cascade.

Russian Gas Centrifuge

The gas centrifuge developed by German scientists in Russia is constructed on a different principle. of the rotor is a magnetic damping device, thus avoiding any mechanical contact between the rotating and non-rotating parts.

The gas is led in and removed in the same way as in the centrifuge described above, through a non-rotating shaft and through two Pitot tubes at the upper and lower ends of the rotor. One Pitot tube is placed in an end chamber, the other causes the countercurrent of gas inside the rotor by reducing the rate of rotation of the gas.

The centrifuge is driven by a synchronmotor, placed inside the vacuum jacket, whose stator acts

on a steel plate connected with the lower end of the rotor. The gas blowing out of the upper end of the rotor is prevented from entering the vacuum jacket by means of molecular pumps; these are formed by the rotor itself and by helical windings at a short distance.

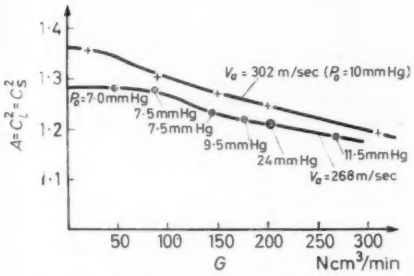

Figure 12. Relation between enrichment, A, and throughput, G, (argon), ($G_o = G_u = G/2$, (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

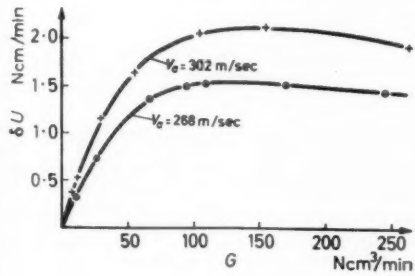

Figure 14. Relation between separation potential, δU, and throughput, G, (xenon); $\left[\delta U = \frac{G}{2}\left(\sqrt{A}-1\right)^2\right]$ (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

Results

It was first established experimentally[9] that the enrichment in the thermally-controlled counter-current centrifuge is multiplied by the factor $L/2r_2$ for the static case, with no throughput, with optimum temperature differences, that is when convection speeds are optimum. Some of the results for different pressures and peripheral speeds, and mean temperatures, obtained for isotopes of xenon and argon, are given in *Figures 8* and *9*.

Next, the dependence of the enrichment A on the throughput G was measured, varying the temperature differences for each throughput to achieve maximum enrichment. The results are shown in *Figures 10* to *12*.

The relation found between A and G enabled us to calculate the separation potential δU, shown in *Figures 13* to *15*. The shape of the δU curves is

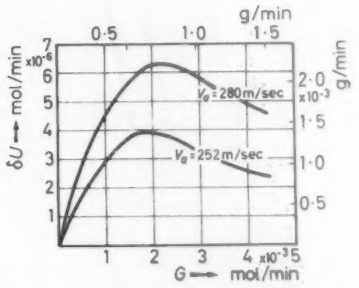

Figure 13. Relation between separation potential, δU, and throughput, G, (UF_6) (BEYERLE, K. *and* GROTH, W.[14]; *courtesy North Holland Publishing Co.*)

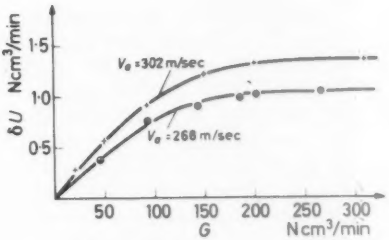

Figure 15. Relation between separation potential, δU, and throughput, G, (argon); $\left[\delta U = \frac{G}{2}\left(\sqrt{A}-1\right)^2\right]$ (GROTH, W. *and* WELGE, K. H.; *courtesy Z. phys. Chem.*[14] (1959) **19** 1)

influenced by the molecular weight of the gas, the peripheral speed, and the ratio $L/2r_2$.

For uranium hexafluoride there was a sharp maximum in the separation potential, amounting to 75 per cent of the theoretical maximum. For xenon, it remained constant over a wide range of throughput values, and amounted to only 36 per cent of the maximum value. For argon, no drop in separation potential could be observed for the highest throughput values which could be achieved experimentally; the maximum experimental value of the separation potential amounted to about 30 per cent

Table 2. Separation potential

Type	*L cm*	r_2 *cm*	$L/2r_2$	ωr_2 *m/s*	*U kgU/a*	*Specific electrical consumption kWh/kgU*	*Specific investment cost DM/kgU/a*
UZ 1	40·0	6·0	3·33	302	0·582	12,050	17,200
UZ IIIB	63·5	6·7	4·74	302	0·935	8,380	11,950
ZG 3	66·5	9·25	3·60	302	0·97	6,300	10,300
ZG 5	113·0	9·25	7·03	302	1·64	3,710	6,100
ZG 6	240·0	20·0	6·0	302	3·5	1,750	2,860
				340	5·32	1,150	1,880
ZG 7	316·0	22·5	7·03	302	4·77	1,285	2,100
				340	7·25	845	1,380
Diffusion Process						9,000	2,350

of the theoretical maximum. These great differences result from the dependence of the separation potential on the flow profile, which is determined by the pressure gradients, which depend on mass. It is found that the heavier the mixture of isotopes to be separated the higher relative separation potentials can be achieved experimentally with the gas centrifuge, so that for this reason too it is particularly suitable for increasing the concentration of uranium isotopes.

The experimentally determined separation potentials make it possible to calculate the specific investments and thus to compare the method with the gas diffusion process[14]. *Table 2* gives the separation potentials achieved experimentally in rotors in use and under construction, amounting to 75 per cent of the theoretical maximum, the specific investment costs and the specific electrical investments, which may be compared with the specific investments for the gas diffusion process. It shows that for the *ZG 5* model in use up to now, the specific investment cost is still higher than for the gas diffusion method, but that the specific electrical investment, which at European prices for electric power is a vital factor, is already $2\frac{1}{2}$ times less. In the *ZG 7* model, which has a peripheral speed of 340 m/sec, the specific electrical investment is reduced by more than ten times, and the specific cost by 1·7 times, as compared with the gas diffusion method. In making this comparison, a gas centrifuge's electrical power consumption is assumed to be 700 W and the price of a centrifuge, with accessory equipment, 10,000 DM. It seems quite possible, from the construction angle, to reduce the power consumption to 500 W and the cost per centrifuge, when manufactured in large quantities, to about 5000 DM, when the process would compare even more favourably with the gas diffusion process. It is not to be wondered at, therefore, that experiments on isotope enrichment with centrifuges are being intensively pursued in many countries.

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SOME PROPERTIES AND PROBLEMS OF THE LIQUID STATE

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The difficulties of obtaining accurate knowledge of the atomic distribution in liquids are pointed out. Three methods of studying liquid structure, by statistical mechanical theories assuming an interaction function, by direct geometrical methods and by using 'cell theories' are described, and the electrical conductance of liquid metals is discussed.

WHEN writing of the theory of liquids it is almost an established practice to contrast, with regret, its great difficulty with the relative easiness of gas and solid theory. There is good reason for this. Being a condensed form of matter, the liquid state loses the simplicity conferred on gases by their comparative lack of intermolecular attraction; but, on the other hand, this is not compensated, as in the solid state, by the simplification of a regular crystal structure.

Atomic Distribution in Liquids

It is a feature of modern solid state physics that properties are explained with the help of a detailed knowledge of structure revealed by x-ray and neutron diffraction. Recent articles in this journal on cooperative magnetism offer a good example. Diffraction techniques have also been applied to liquids since 1915 but the results are harder to interpret and use. The essence of the method is as follows: a well defined monochromatic beam of x-rays is directed on to the free surface of the liquid or on to a specimen contained in a thin walled holder. The angular distribution of the scattered radiation is measured with a counter or by photographic methods. After some correction these data yield an angular distribution of coherent scattering exemplified by *Figure 1*. To the right of the rather broad peaks, the curve becomes indistinguishable from that due to the scattering from a random assembly of atoms. This is in marked contrast to the series of sharp lines given by a crystal and indicates at once that the long-range order characteristic of crystals is absent. Consequently nothing analogous to a unit cell can be inferred and the structure must be represented another way.

Consider a spherical shell of thickness dr and radius r, centred on any molecule in the liquid, and let n_r be the number, averaged over time, of the molecules in the shell. Then the equation

$$4\pi r^2 \rho_0 g(r) dr = n_r \qquad \ldots (1)$$

defines a function, $g(r)$, called the radial distribution function; ρ_0 is the mean number of molecules per unit volume in the liquid.

A theoretical connection exists between $g(r)$ and the intensity distribution of *Figure 1* and $g(r)$ can be inferred—not without misgivings on the part of some workers—from a suitable integration of the scattering distribution*. The result is exemplified in *Figure 2*. Up to about 3 Å, $g(r)$ may be taken as zero and at 4·6 and 9·0 Å there are peaks. These facts reflect the strong repulsive force that prevents too close an approach of the atoms, and the distinct tendency for nearest and next-nearest neighbours to arrange themselves at a definite distance from the centre atom. Thus there is a vestige of order which, however, ceases to be apparent after a few interatomic distances.

This conclusion which applies to all monatomic liquids, metallic and otherwise, is about as far as the diffraction techniques will lead. They do not reveal what the immediate environment of an atom is actually like.

Statistical Mechanical Theories

However, this detailed knowledge is not required for a rigorous theoretical approach to the equilibrium properties of liquids; the radial distribution function will suffice. For example, the equation of state has been derived by H. GREEN in the following form[4,6]

$$pV = RT - \frac{\rho_0^2 V}{6} \int_0^\infty g(r) \frac{\partial \psi(r)}{\partial r} \, 4\pi r^3 dr \qquad \ldots (2)$$

In this equation, which is rigorous, $\psi(r)$ is the

* The experimental and theoretical methods are outlined in Reference 1 and discussed in detail in Reference 2.

potential energy function for a pair of atoms separated by a distance r. The first term on the right dominates at low densities and gives the ordinary law for rarefied gases; the second dominates in

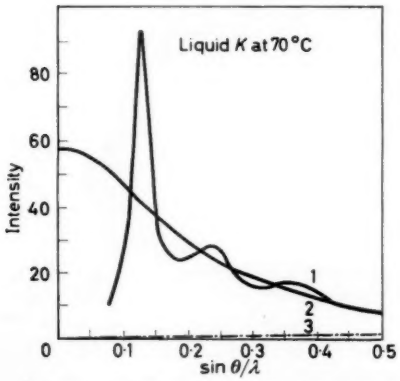

Figure 1. Angular distribution of scattered radiation intensity from liquid potassium— 2θ is scattering angle, λ is the wavelength, (1) corrected experimental curve, (2) scattering from assembly of randomly distributed atoms and (3) incoherent scattering curve (subtracted from observed curve). (THOMAS *and* GINGRICH, *1938*; *courtesy J. chem. Phys.* (1938) **6** 411)

dense fluids and shows the importance of the radial distribution function (r.d.f.) to liquid theory. Other thermodynamic properties have similar equations.

Unfortunately the r.d.f.'s furnished by diffraction experiments are not accurate enough to substitute in *Equation 2* to find the equation of state, and much recent and current work is devoted to calculating $g(r)$ from first principles, *i.e.* from statistical mechanics and an assumed interaction function ψ. It is here that much of the difficulty enters. The methods of circumventing the difficulties must be pursued in specialist works[3,4], but here we shall indicate briefly what the nature of the difficulty is.

A potential function often considered in this and other liquid state work has the form shown in *Figure 3*. It represents attraction at large distances and repulsion at small. Analytically this may be expressed

$$\psi(r) = a[(b/r)^m - (b/r)^n] \quad \ldots (3)$$

where a and b are adjustable parameters. For simple non-polar molecules, such as rare gases, $m = 12$, $n = 6$ (the Lennard-Jones potential). For metallic liquids whose bonding is more complicated smaller values of both m and n are better[5], leading to less steep sides to the potential well.

Suppose, then, that ψ is known and let

$$n^{(2)}(r_{1,2})\,\mathrm{d}\mathbf{r}_1\mathrm{d}\mathbf{r}_2$$

stand for the number of pairs of molecules of which member 1 is in the volume element $\mathrm{d}\mathbf{r}_1$ and member 2 is in $\mathrm{d}\mathbf{r}_2$, and $r_{1,2}$ is the distance between the volume elements; $n^{(2)}$ differs only by a constant factor from $g(r)$. Let $n^{(3)}$ be the corresponding quantity for triplets of molecules at volume elements $\mathrm{d}\mathbf{r}_1$, $\mathrm{d}\mathbf{r}_2$, $\mathrm{d}\mathbf{r}_3$. Now there is no difficulty in deriving, from statistical mechanics, integral expressions for $n^{(2)}$ and $n^{(3)}$, but the integrals are too complex to evaluate even with modern computing techniques. However, an equation—also virtually insoluble in practice—can be constructed to connect $n^{(2)}$ and $n^{(3)}$. To proceed further, this equation is reduced to one involving $n^{(2)}$ only by using a hypothesis called the 'superposition approximation'. This asserts that the probability of any triplet configuration of molecules is equal to that of the three constituent pairs occurring separately, *i.e.*

$$n^{(3)}(1,2,3) = \frac{n^{(2)}(1,2)n^{(2)}(2,3)n^{(2)}(3,1)}{\rho_0^3} \quad \ldots (4)$$

$n^{(3)}$ can now be eliminated from the theory and an equation for $n^{(2)}$ results[6,7]. This equation can be solved, albeit with difficulty and approximation. It is now apparent that the obstacles are those of mathematics, not physics. If the widely used superposition approximation could be sufficiently validated, or if its use could be avoided in a manner both accurate and practicable, the theory of equilibrium properties of liquids would presumably be completely successful. Such matters are still under discussion[8].

A Direct Approach to Liquid Structure

Another approach to liquid theory has been made recently by BERNAL[9] with the object of examining the geometrical relation between near neighbours. If this were known the r.d.f. could be inferred.

Near neighbours may be identified as follows: let straight lines be drawn from atom A to all others B_1, B_2 . . . and let planes bisect these lines. Consider the smallest convex polyhedron round A made by these planes. Then the atoms B_1, B_2 . . . B_{n_1} corresponding to the n_1 sides of this polyhedron are the geometrical neighbours[10] of A. In a simple monatomic crystal the polyhedra are all the same; in a structure of close packed spheres, $n_1 = 12$. In an irregular structure, as illustrated in *Figure 4*, the polyhedra are various and n_1 has a distribution. However, if the irregular system is densely packed —as liquids at the melting point are —n_1 will not be far from 12.

Bernal has devised several ways of determining the polyhedra of an irregular system and estimating n_1. One which is simple and illuminating is as follows: small spheres of plasticene were coated with chalk to prevent sticking and packed irregularly together in a rubber bag. Compression in a pressure vessel made the plasticene into a solid lump, the spheres becoming polyhedra. The separate polyhedra could then be prised from the lump and examined for shape and number of faces (*Figure 5*). The polyhedra were various and irregular, the faces were predominantly pentagonal (this would be impossible in a monatomic crystal), and the average value of n_1 was 13·3.

A dense but irregular packing of spheres—represented by a set of irregular neighbourhood polyhedra such as that just considered—has a volume about 10 per cent greater than the same number of spheres closely packed into a crystal structure. It seems impossible to pack spheres into an intermediate volume. This has an obvious bearing on the phenomenon of melting which, according to Bernal, is a structural transformation from a regular structure to a homogeneous but essentially irregular one. The impossibility of forming a homogeneous

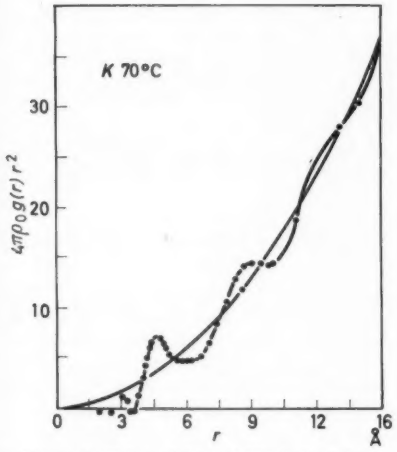

Figure 2. Value of $4\pi\rho_0 g(r) r^2$ derived from Figure 1—the smooth parabola would be obtained if $g(r) = 1$. (THOMAS *and* GINGRICH, *1938*; *courtesy J. chem. Phys.* (1938) **6** 411)

assembly of volume between that of close packed order and close packed disorder corresponds to the thermodynamic inaccessibility of the region between supercooled liquid and superheated solid discussed recently by BORELIUS[11]. Furthermore, as the temperature of the liquid is increased, thermal expansion is accompanied by successive changes in the shape and faces of the neighbourhood polyhedra,

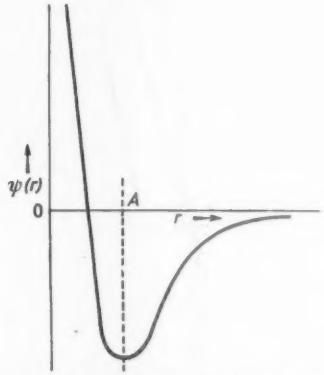

Figure 3. Interatomic potential energy curve —A is the equilibrium separation

i.e. by progressive structural change. Thus Bernal regards a liquid not as a single phase but as a series of successive phases. The application of this idea to phenomena in the critical region is pursued in the reference cited[9].

Bernal's hypothesis is that a liquid is a 'homogeneous, coherent, and essentially irregular assemblage of molecules containing no crystalline regions or holes large enough to admit another molecule'[9]. Coherent, in this context, means that every molecule is physically linked with every other molecule either directly or through intervening ones.

To connect this logically with the statistical mechanical theories it would be necessary to compute the r.d.f. or some other fundamental quantity. Consider, for example, a spherical shell centred on an atom and bounded by radii r_0 and $\sqrt{2}r_0$ where r_0 is the distance of closest approach of atoms, idealized as spheres. In a close packed structure the nearest neighbours of an atom will lie round it in a shell of about this size. Now put a point, representing an atom, at random in the shell; then another at random—which is allowed to remain where it is provided its distance from the first does not happen to be less than r_0. Add more and more points until one more cannot be put in without its being too close to another. This now provides an irregular set of near neighbours for the atom at the centre. This could be repeated over and over again to build up a statistics. Further, for any given arrangement the potential energy could be calculated for an assumed $\psi(r)$.

Such procedures can be elaborated and adapted to electronic computing and they are not confined to the first shell of neighbours. This work is in progress but Bernal has already indicated that the structures so obtained lead to radial distribution functions with first and second peaks in the places, and of the sizes, obtained in diffraction experiments[8].

It must be remembered that the structures so envisaged are static such as an instantaneous photograph might reveal. Any given atom is not in an equilibrium position as in a crystal. This leads to a continual movement and interchange of neighbours which is a *sine qua non* for the characteristic diffusion and fluidity of liquids.

An alternative hypothesis about the structure is that a liquid consists of very small quasi-crystalline regions separated by layers of greater disorder[12]. In principle this could be distinguished from a homogeneous irregular system by diffraction methods but this may be technically impracticable.

Cell Theories: Furukawa's Model

Between the rather rigorous and abstract statistical mechanical method and the direct geometrical approach to irregular structure lies a group of theories called ' cell theories '. In these, each atom in a liquid is supposed to be confined by its neighbours to a cell where it may move subject to the prevailing forces exerted by the neighbours. These forces are derived from a potential function calculated by assuming that the neighbours are all at rest in equilibrium positions in a lattice, *e.g.* a face-centred cubic lattice.

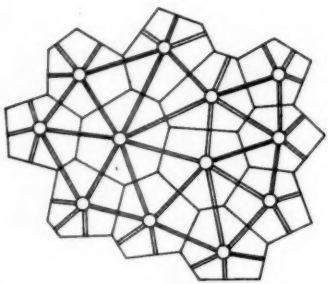

Figure 4. Two dimensional representation of the polyhedra for irregularly distributed neighbours

The simplifying value of these assumptions can be seen in the following way. According to statistical mechanics, all the thermodynamic properties of any system of N molecules can be computed if Z_N, the partition function, is known. The expression for Z_N is[3]

$$Z_N = (N!\lambda^{3N})^{-1} \int e^{-\Phi/kT} \, d\mathbf{r}_1 d\mathbf{r}_2 \ldots d\mathbf{r}_N,$$

$$\lambda^2 = h^2/2\pi mkT \qquad \ldots (5)$$

Here Φ is the potential energy of the whole system and the integral is over all possible configurations of the molecules. This integral is just as intractable (for liquids) as the expression for $n^{(2)}$ previously referred to. However, on the cell theory, Φ can be resolved into Φ_0, the potential energy of the system with all molecules at rest in their equilibrium positions, plus the potential energy of the molecules due to their displacements within the cells. As all the cells are equivalent, the integral can readily be converted to the form

$$N! \, (v_f)^{N_e} e^{-\Phi_0/kT},$$

where

$$v_f = \int e^{-\phi/kT} dv,$$

the ϕ now being the potential energy function associated with displacement in the cell and the integral being over the cell volume. The quantity v_f is of dimension L^3 and is called the free volume. If ϕ were zero, v_f would simply be the volume of one cell and the atom would move freely within it. If ϕ increases away from the centre of the cell, the atom is constrained nearer the equilibrium position. Since the free energy of a system is given by

$$F = -kT \log Z_N,$$

we have

$$F = -NkT\left[\log v_f + \log \frac{(2\pi mkT)^{3/2}}{h^3}\right] + \Phi_0 \qquad \ldots (6)$$

and thermodynamic behaviour can be deduced from this.

The cell theory was first employed extensively by LENNARD-JONES and DEVONSHIRE[13] and has been developed in several ways since, *e.g.* by considering various numbers of neighbours, by allowing more cells than molecules, and by allowing more than one molecule per cell. By suitable assumptions of this sort, reasonable agreement with experiment can be achieved for the thermodynamic properties of the rare gases[14]. Cell theories, though obviously based on an approximation, are favoured by workers who prefer an easily visualizable model to correlate and guide experimental work.

As an example of the last mentioned attitude, some very recent work by FURUKAWA is of interest[15]. Furukawa first points to several similarities in the r.d.f.'s of different liquids which lead him to suggest a simple model for all monatomic liquids. For

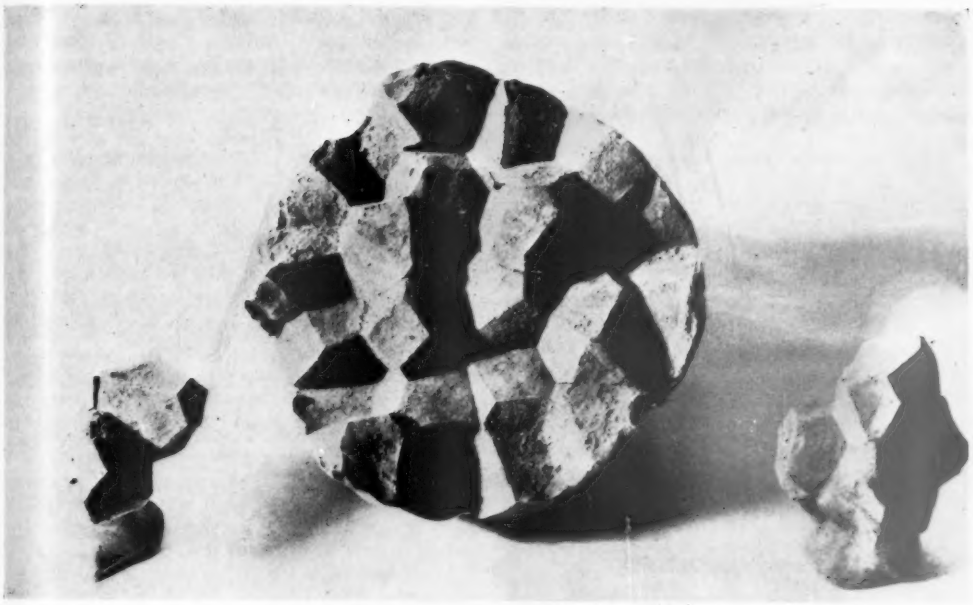

Figure 5. Polyhedra showing pentagonal faces (After BERNAL, *loc. cit.)*

example, the abscissae of the second and first peaks in diagrams like *Figure 2* are in the ratio 1·9 to 1 for a wide variety of liquids including rare gases and metals. Now the number of near neighbours, n_1, can be calculated from the area under the first peak. This has often been done but it is difficult to obtain reliable values, partly because of experimental error and partly because some decision is required about where the appropriate area stops; n_1's from 8 to 11 have been reported by different workers. Furukawa states, however, that if a consistent procedure is applied to all measured intensity distributions $n_1 = 10{\cdot}5$ to $11{\cdot}0$ for almost all elements. Exceptions are Ga, Zn, Sb, Li. The mean value of n_1 is 90 per cent of that of a close packed crystal. The consistent procedure may itself have a systematic error, but the interesting point is that the n_1's are similar for many liquids. This is compatible with a theory, like Bernal's, in which the structure is homogeneous, irregular, and close packed in all simple liquids for geometrical reasons.

Now let r_1, r_A be the abscissae in *Figure 2* corresponding, respectively, to the first peak and to a point on the left-hand slope of the first peak at 30 per cent of its height. Furukawa points out that $(r_1/r_A)^3 = 1{\cdot}5$ for almost all of the nineteen liquids he considered, *i.e.* the shapes of the first peaks are similar. If r_A is now defined to be the distance of closest approach, this leaves an atom with a probable radius of movement of $(r_1 - r_A)$. An approximate expression,

$$v_f = \frac{4\pi}{3}(r_1 - r_A)^3$$

is therefore adopted for the free volume and the atom is supposed to move freely within this space. This v_f can be substituted in *Equation* 6 and the consequences of this semi-empirical version of the cell theory worked out. Furukawa shows that this simple model correlates several properties of metallic and rare gas liquids, *e.g.* the r.d.f.'s, the expansion on melting, the entropy at the melting point, the self-diffusion.

Metallic Liquids: Electrical Properties

The considerations of the previous sections, and the basic formulae, should apply to metals and non-metals though most of the applications have been to non-metals. However, the defining characteristics of metals are connected with their free electrons and show up in electrical and thermal conductivity, optical properties, and so on. Let us therefore consider the electrical conductivity of monovalent metals.

According to contemporary conductivity theory, electrons pass freely through a perfectly ordered structure, and resistance is caused by disorders, either thermal vibrations or localized crystal imperfections. The disorder introduced when a solid

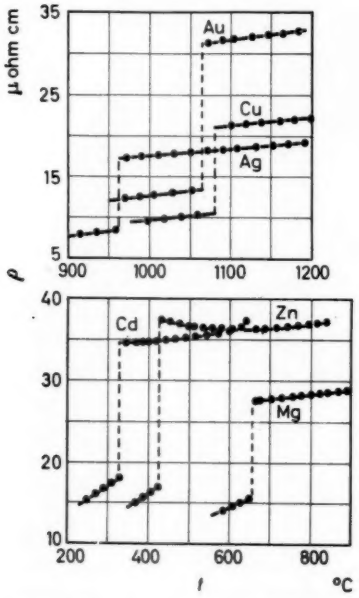

Figure 6. Increase in resistivity at the melting point of metals (after ROLL *and* MOTZ, *1957)*

melts should therefore increase the resistivity. This has long been known for a fact, and the increase is usually by a factor 1·5 to 2. Some recent results are shown in *Figure 6*. As the temperature rises, disorder increases partly because of increased thermal motion and partly because of the structural changes consequent on expansion. The electron mean free path decreases and in most cases this shows up at first as a linear rise of resistivity with temperature, followed by a steeper rise. As the density decreases more and more, and the critical state is approached, the structure becomes less coherent, finally disintegrating into the vapour-like state with very high resistivity. The whole process can be followed with mercury which, under a pressure of several thousand atmospheres, can be maintained in the liquid state up to ~ 1500°C (see *Figure 7*).

Let ρ_L, ρ_S be the resistivities of the liquid and solid at the melting point. Since $\rho_L > \rho_S$ on account of the disorder, ρ_L/ρ_S should be connected with the entropy of melting. Such a phenomenological explanation of the resistivity increase was first given by MOTT[16] whose equation

$$\rho_L/\rho_S = e^{80\Delta S} \qquad \ldots (7)$$

has been widely used. ΔS is the melting entropy in k joule deg.$^{-1}$ mole^{-1}. This equation gives excellent agreement for the noble metals, but less good for the alkali metals. However, it is based on two assumptions of questionable validity: (*a*) the structural disorder characteristic of liquids hardly affects the resistivity at all, and (*b*) the vibrational disorder introduced at melting—which does affect the resistance—can be calculated from ΔS.

Even supposing that the problems of liquid structure had been resolved, a complete theory of electron flow properties in metallic liquids would in

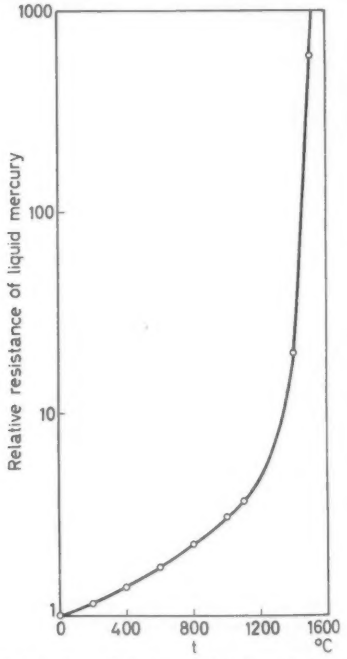

Figure 7. Relative resistivity of liquid mercury at 1870 atmospheres pressure—the critical temperature is about 1460°C (BIRCH, *1932*)

principle require a knowledge of (*i*) the electron states in the liquid; (*ii*) the thermal motion of the ions; (*iii*) the interaction between them. This is a formidable programme towards which only initial steps have been taken. For example, the energy

levels of electrons in one-dimensional models of liquids have been computed by LANDAUER and HELLAND[17] and by EISENSCHITZ and DEAN[18], and the frequency distribution of vibrations of a disordered one-dimensional chain of atoms has been calculated by DEAN[19]; but these theories do not lead to anything directly comparable with experiments.

A most thorough attempt to deal with electron flow properties in liquids has recently been made in a series of papers by GUBANOV[20]. No critique of the theoretical methods used seems yet to have appeared and probably the approximations used make the results applicable only to a limited number of metals. However, formulae for resistivity, thermoelectric power, and so on, do actually emerge and we shall therefore conclude this article with a brief account of the ideas.

First, approximate wave functions for electrons in a structurally disordered liquid are derived and the electrons are represented by wave-packets of dimensions similar to the volume in the liquid over which approximate short range order extends. The structural disorder itself is shown to be responsible for some resistance to the motion of electrons under an applied electric field. In addition however, the ions are supposed to be thermally vibrating and this gives rise to resistance as in a solid—'electron–phonon interaction'. In a crystal, the permissible interaction of free electrons and thermally vibrating ions is restricted by quantum selection rules. According to Gubanov, these rules are relaxed in the disordered liquid, leading to an extra term in the electrical resistance—'phonon–liquid interaction'. Finally, localized disorders such as impurities and cavities are allowed for. All these sources of resistance are combined into an expression for the electron mean free path. Given this expression, standard methods of calculation yield the resistivity thermal conductivity, and other properties. For example the resistivity can be represented by a sum of terms:

$$\rho = \rho_1 + \rho_2 + \rho_3$$

such that ρ_1 and ρ_2 derive from the structural disorder and would vanish in the solid, and ρ_3 is a term proportional to temperature arising from the electron–phonon interaction just as in a crystal. The qualitative ideas, which seem to derive from an early discussion by SCHUBIN[21], are valuable, but the relative importance of ρ_1, ρ_2 and ρ_3 in real liquids has yet to be determined.

Conclusion

This selection of liquid state problems is only a very small one, but it should indicate that fundamental questions, both mathematical and physical, are still open. This applies equally to the many fields of liquid state physics which there has been no space to mention in this paper. The celebrated intractability of liquid state problems still exists but is slowly yielding.

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SCIENCE IN PARLIAMENT

Minister for Science

THE APPOINTMENT of a Minister for Science is greatly to be welcomed. Lord HAILSHAM, as Lord Privy Seal and Minister for Science is to be responsible to Parliament for the Council for Scientific and Industrial Research, the Medical Research Council, the Agricultural Research Council, the Overseas Research Council and the Nature Conservancy, and is chairman of the five Privy Council Committees to which they report. He will also exercise ministerial functions under the Atomic Energy Acts, and will exercise general supervision over the programme of space research at present being devised under the direction of the Steering Group. Other Ministers remain responsible for the scientific establishments within their own Department, but the Minister for Science is responsible for broad questions of scientific policy outside the sphere of defence, and is advised by the Advisory Council on Scientific Policy on general questions which relate to the whole field of Science (Prime Minister, 30.10.59).

The appointment caused members of the House of Commons some concern due to Lord Hailsham being a member of the Upper House. A number of questions were put to the Government as to who should answer questions on particular subjects, and the Prime Minister informed the House on November 3 that the Minister of Health would answer about the Medical Research Council and radiobiological hazards; the Minister of Agriculture about the Agricultural Research Council and Nature Conservancy; the Minister of Education questions about the atomic energy and the Department of Scientific and Industrial Research and general scientific matters, and the Minister of Aviation questions about Space Research, in each case the Minister answering 'as representing the Minister for Science'. Also where questions about atomic energy development related to matters where another Minister is responsible, that Minister will answer them; *e.g.* questions about nuclear powered shipping will be answered by the Minister of Transport, and about nuclear power stations by the Minister of Supply. Questions on nuclear defence will be the province of the Minister of Defence or appropriate Service Minister, and those dealing with research and development of these weapons by the Minister of Aviation, either on his own account or representing the Minister of Science. Mr T. F. PEART (Socialist, Workington) asked whether the Minister for Science would co-ordinate research and also deal with scientific policies in universities.

Motor Vehicles—Noise and Smoke

Questions were asked about the control of noise and smoke from motor vehicles. According to the Minister of Transport, technical officers from the Ministry are collaborating with the International Standards Organization to establish practical methods of measuring traffic noise. New methods were provisionally agreed at Stuttgart last summer, and the methods proposed are now being tested. At the Ministry's research depot at Hendon there is a machine for testing the noise of motor cycles. Mr R. Gresham COOKE (Conservative, Twickenham) suggested that the regulations concerning the Motor Vehicle Construction and Use Regulations should be amended to simplify the task of the courts in establishing the emission of excessive diesel engine smoke.

Meat Research Institute

A small temporary station is to be established near Cambridge to expand the research on meat already being done at the Low Temperature Research Station and elsewhere; it should be in operation by the end of next year. A proposal for a permanent centre for meat research is under consideration. (Mr J. B. GODBER (Conservative, Grantham) 2.11.59.)

Nuclear Propulsion of Merchant Ships

In reply to various questions, the Rt Hon. Ernest MARPLES said that a report had been received from the sub-committee which was appointed to make a technical appraisal of the different reaction systems designed for use in merchant ships, and their recommendations are receiving consideration. Mr J. HAY (Conservative, Henley) stated that the particular gas-cooled reactor being developed by the Atomic Energy Authority for land application is not, on present information, economic in the smaller sizes required for marine propulsion.

Site for Thermonuclear Station

Mr E. HUGHES (Socialist, S. Ayrshire) criticized the United Kingdom Energy Authority for seeking to site a new thermonuclear station in the congested county of Oxfordshire, when there would appear to be every advantage in building it in Scotland, with its wide open spaces, clean air, adequate water supplies, availability of labour and skilled scientists.

SURVEY

Neutron Project at Harwell

The new neutron 'time of flight' laboratory at Harwell provides information on the interaction of neutrons with nuclei, and will be used to give data for reactors at present being designed, for paper studies of 'exotic type' reactors to foretell their efficacy, to anticipate problems in working reactors or those under design, and last, but not least, for pure research in nuclear physics. The behaviour of neutrons of known velocities when they encounter materials employed in the construction of reactors and the rates of reactions inside a reactor will be examined, and it will be possible to calculate the condition of the reactor after it has been running for several years.

The basic principle of this 'time of flight' laboratory is that neutrons from a pulsed source are ejected along an evacuated tube to a detector which records their interaction with some material and, by the use of an electronic timing machine, the velocities, and therefore the energies, of the neutrons are simultaneously recorded. A specimen containing nuclei to be examined is placed in the neutron beam and its reaction with neutrons of different energies recorded. For accurate measurements the flight path should be long, and therefore a very powerful source of neutrons is required. The apparatus consists of three main sections; the travelling wave linear accelerator, to produce bursts of electrons, a booster or reactor to produce neutrons, and the vacuum tube and detector.

A radio frequency waveform is generated by a magnetron oscillating at 2998 Mc/s and is amplified by six klystron amplifiers, each producing 6 MW of r.f. power and each feeding a section of the six section accelerator (*Figure 1*). Since this power is generated only during short pulses in order to produce finally short bursts of neutrons, the mean power output of the klystrons is only 9 kW per valve. Electrons are injected from an electron gun into the first section of the accelerator which consists of an evacuated wave guide containing 'corrugations' which control the phase velocity of the travelling electromagnetic wave. The electrons are formed into bunches each of which is accelerated by one wave-front. The phase velocity of the waves is such that the electron bunches are smoothly accelerated till their energy is 25–35 MeV at the output end of the machine. Each machine pulse produces about 1000 electron bunches or more, very close together like beads on a string. On leaving the accelerator the electrons fly down an evacuated drift tube at the end of which they enter the neutron producing target (*Figure 2*) where they strike a mercury target which serves the dual purpose of producing x-rays and removing the heat caused

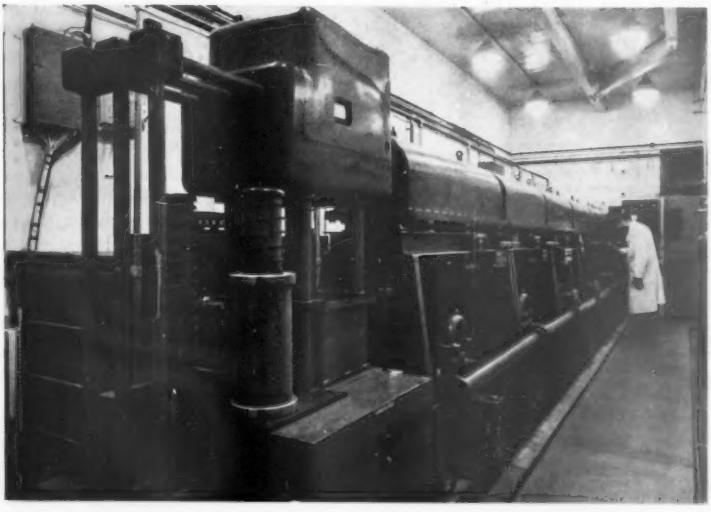

Figure 1. 25 MeV electron linear accelerator. (*Courtesy U.K.A.E.A.*)

by stopping the beam. The x-rays are then absorbed in uranium to produce neutrons by photo-disintegration and photofission. The size of the neutron output is increased ten times by using a sub-critical U^{235} assembly (the booster) so that 5×10^{17} neutrons per second are liberated during a machine pulse. The neutrons are then shot down a vacuum tube and timed to an accuracy of one ten millionth of a second.

There are at present two target rooms and a third one will be in operation shortly. The main target room containing the booster has eight evacuated flight paths emerging from it, though this number can be increased. The lengths range up to 300 metres and the speeds of the neutrons vary from 500–5,000,000 m/s. The information is therefore for neutrons of higher energies than those produced by thermal reactors, and should overlap with the information obtained using Van de Graaf accelerators.

There are comparable electron linear accelerators in, for example, France, the U.S.A. and the U.S.S.R. The novel features of this project are the use of the sub-critical multiplying assembly to augment the neutron intensity, and the provision of a special building and flight path layout for ' time of flight ' work. Apparently the most difficult problem was to create a large enough source of neutrons, as a large number will be lost en route, and this machine is capable of liberating 100,000 million neutrons in a pulse lasting one quarter of a microsecond; they claim at Harwell that this is the most powerful pulsed source of neutrons in the world.

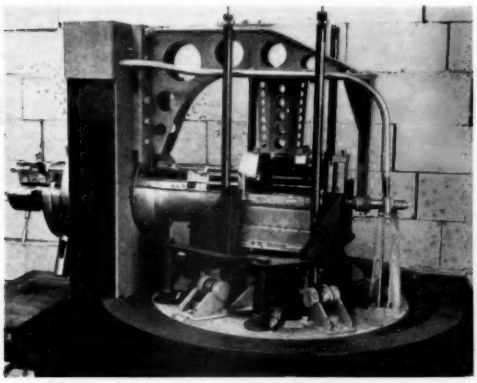

Figure 2. Model of the neutron booster (Courtesy U.K.A.E.A.)

Research on Glass: the Laboratories of Pilkington Brothers Limited

One of the most interesting departments at Pilkington's research laboratories is that dealing with optical glass. Pilkingtons claim that their product is now at least equal to, if not better than, German optical glass. A new process for casting optical glass has been developed. The method is a continuous one, as in the case of steel, whereby molten glass is allowed to flow down a tube made of platinum and is at the same time continuously stirred. Refractive indexes are taken constantly as the glass is cast and small errors can be corrected by altering the heat treatment schedule.

In another department the physical and chemical properties of a wide range of glass compositions—in this case not optical glass—is being tabulated so that a glass with specific physical or chemical properties can be made at will. Physical investigations on both production and experimental compositions include viscosity at high temperatures, the range of temperature at which the glass will crystallize, the determination of Young's modulus by a method using stationary sound waves and the examination of stresses and strains in glass by photoelastic techniques.

A good deal of attention is being paid to the valency condition of the ions in a glass. Magnetic susceptibility measurements can in certain cases determine the amount of covalency and radiation studies could perhaps give the answer to some of these problems. It may well be that colour changes in glass are due to changes of energy level induced by the introduction of ' foreign ' ions such as cobalt, *etc.* and not due to the actual presence of these ions themselves. If this theory is correct then it may be possible to induce a similar effect by suitable irradiation. Radioactive tracer studies are used for other purposes such as determining the degree of mixing in large glass tanks (these are about the size of medium or large swimming pools).

The study of heat transfer in glass is important, both from the point of view of the melting and of the colour of the glass. The temperature gradient inside a glass tank and its refractory linings has been calculated when these are in a stationary condition and attempts are now being made to produce similar equations for non-static conditions. The heating of glass tanks is a difficult problem. The standard method uses producer gas which heats the top surface of the glass and only about ten per cent of the total melt is drawn off in each cycle (approximately 20 minutes). This, in fact, means that 90 per cent of the glass is being continuously

Figure 3. General view of equipment racks of the experimental electronic telephone exchange. 'A' is the magnetic drum. (By courtesy of H.M. Postmaster General)

reheated with a wastage of large amounts of fuel. But it is claimed that this method gives a better quality glass and heat transfer studies are therefore designed to investigate the possibility of drawing off larger percentages of the melt in each cycle without, of course, any deterioration in the quality of the glass. This may lead to good glass being produced with strict temperature and composition control but using very much smaller and more economic tanks.

The post-war years have seen a new industry emerge, that of fibre glass. Fibre glass is used for insulation, reinforcement and many other unique applications. One section of the research laboratories is devoted entirely to the preparation and testing of the properties of fibre glass. The strength of fibre glass is almost phenomenal: it has a tensile strength of half a million pounds per square inch but one of the problems is the protection of the glass against the action of ordinary salt water which can cause great weakening of the fibre. Usually this is done by resinous materials.

To house these and the many other research activities at Pilkington Brothers, new research premises are in the course of construction and will be opened some time next year. They will accommodate about 500 staff, almost double the present number.

A Prototype All-Electronic Exchange

An experimental all-electronic exchange has been installed at the Post Office Research Station at Dollis Hill, London, and is now undergoing stringent testing. The extensive research leading to its setting up has been carried out by the Post Office in co-operation with five of the principal manufacturers of telephone exchange equipment, and this pooling of facilities and research staff for a common project has of course greatly speeded up the work. Further, the wastage of manpower and materials which often occurs on account of overlapping of individual research projects has been avoided.

The present laboratory model (*Figure 1*) permits of telephone calls within the research station and also into the London public telephone system. If it comes through its tests satisfactorily it will be used as the basis for building a public exchange of about 1000 lines at Highgate Wood in North London. Before this equipment, the first all-electronic telephone exchange in this country, is installed for the public to use, it will undergo a further year's testing with artificial traffic. It is hoped to have the exchange open to use by the general public about two years after tests are completed on the experimental model at Dollis Hill. If the Highgate Wood exchange is satisfactory, new exchanges will be built on all-electronic lines instead of the earlier electro-mechanical principles.

As its name implies, the all-electronic exchange differs from existing electro-mechanical exchanges in that conventional switches are replaced by electronic devices such as transistors and special valves, which can similarly turn a current on and off. The advantages of the new type of exchange lie in the facts that an electronic switching system or 'gate' involves no moving parts, so that maintenance costs are lowered and reliability increased; and that it operates much more quickly than an ordinary switch. This speed of operation leads to the most significant advance made in the all-

electronic exchange, the use of a 'time division multiplex system'. In an ordinary exchange a successful call implies a direct electrical path between the two telephones which is maintained continuously for the duration of the call, so that all the apparatus involved in the making of the call is out of action as far as other calls are concerned until this particular one is finished. It was of course always theoretically possible to provide the electrical path only for recurring spaces of time, thus enabling part of the apparatus to be shared among a number of calls. If these spaces of time are long enough and recur frequently enough, speech will be carried with complete efficiency from one subscriber to the other, the discontinuities being so small and so quick as not to be detectable. With ordinary switching systems such an arrangement is not possible; the slowness with which the switches operate would cause the discontinuities to be obtrusive. Electronic switching methods, however, allow a call to be provided with a direct electrical path for 1 microsecond 10,000 times a second, and the quality of speech transmission is quite as high as when the path is maintained continuously. This interlacing of speech circuits into a 'multiplex' permits 100 conversations to be carried on simultaneously through the one main channel (each one of course audible only to the people taking part in it), and a consequent large reduction of apparatus bulk. The time may even come when a new Post Office telephone exchange, in addition to being cheaper to build, will be so small that it can be built underground economically.

Extensive electronic supervisory equipment is of course necessary in use of the time division multiplex, *e.g.* for the opening and closing of the subscribers' individual electronic gates. Other sections of the exchange include apparatus for setting up calls and selecting channels and for translating dialled numbers into signals to operate the appropriate gates. A permanent 'memory', for registering the number of successful calls made by a subscriber, is given by a magnetic drum ('A' on *Figure 1*) on which each subscriber has his own particular part. Temporary 'memories' are given by the drum and by magneto-strictive delay lines, and are used for storing over a short time information such as the number dialled in a particular call.

Apart from lower initial and maintenance costs, greater reliability and decreased bulk, this new type of exchange permits of much greater flexibility of installation, so that the number of subscribers in a given exchange may be easily increased up to a certain limit without fundamentally altering the supervisory and other central sections.

Essay Competition Prizegiving

The prizes for the 1959 Waverley Gold Medal Essay Competition, and for the Essay Competition for Schools and Technical Colleges which this year were given by *Technology* and *Research*, were presented by Sir FREDERICK HANDLEY PAGE at the Royal Society of Arts on Monday, November 2nd. Sir ALEXANDER FLECK was in the Chair.

Figure 4. Sir Frederick Handley-Page presenting the Waverley Gold Medal to Dr T. H. Osgood, American Scientific Attaché, who represented Dr R. A. Gross

The Prizegiving was preceded by a very interesting address by Sir PATRICK LINSTEAD, Rector of Imperial College of Science and Technology on 'The Changing Pattern in Science and Technology'.

The prizewinners were as follows:

Waverley Gold Medal and *First Prize* to Dr ROBERT A. GROSS, Department of Physics, University of California, Berkeley, California, U.S.A. for 'A Study of Combustion in Supersonic Flow' (See *Research* (1959) **XII**, 381).

Second Prize to Mr W. E. BENNETT of the Atomic Weapons Research Establishment, Aldermaston, Berkshire for 'The Generation of Direct Current at High Potentials' (Reprinted in this issue of *Research*).

Under Thirty Prize to Mr B. J. CHALMERS of the Faculty of Engineering, The University of Bristol for 'Engineering Design by Digital Computers' (See *Research* (1959) **XII**, 390).

First Prize in the Schools Competition, Section I, to ROYDEN CLUTTERBUCK of The County Secondary School, Churchdown, Gloucestershire.

Second Prize in Section I to CHARLES N. MOORE of Woodbridge School, Woodbridge, Suffolk.

First Prize in Section II to D. J. CLARE of Wymondham College, Wymondham, Norfolk.

Second Prize in Section II to MALCOLM S. LONGAIR of Morgan Academy, Dundee, Angus.

First Prize in Section III to DEIRDRE A. SPARROW of the S. Herts. College of Further Education.

BOOK REVIEWS

Fluctuation Phenomena in Semiconductors

A. VAN DER ZIEL

(*viii*+168 *pp; 8¾ in. by 5½ in.*)

London: Butterworths Scientific Publications. 35*s*

KNOWLEDGE of fluctuation phenomena in bulk semiconductors and at semiconductor junctions has grown rapidly in recent years. Dr VAN DER ZIEL's authoritative survey, which includes discussions of fluctuations in semiconductor resistors, photoconductors, semiconductor diodes and transistors, will be of great interest to many concerned with the extensive scientific and industrial use of such devices. The reader will find that in addition to its technical importance the subject has great scientific interest and that recent developments depend on very interesting applications of many facets of semiconductor theory.

Dr van der Ziel opens with a useful, short account of the fundamentals of noise measurement. He then gives a concise but clear outline of the basic ideas of fluctuation theory which are to be used throughout the book. In subsequent applications he assumes, as befits a volume in a series of semiconductor monographs, a considerable knowledge of semiconductors: it is no overstatement that the reader is assumed 'familiar with current semiconductor nomenclature, the diffusion equations and the concepts of donors, acceptors, traps and recombination centres'. The reader will frequently find that the original papers demand much less of his previous knowledge of semiconductors and of his powers of understanding than do the concise accounts in the book. Indeed a wider public might have been served had the author used a somewhat broader brush and left the reader to go to the original papers for details. One has to dig rather deeply to get the benefit of Dr van der Ziel's overall picture of the subject and his feeling for the relative importance of his topics. But the author's main aim has been to present a coherent and more or less detailed account of the current state of knowledge of semiconductor fluctuations. In this he has succeeded very well.

To have embodied work only months old at the time of publication is a considerable achievement by both the author and the publishers. C. W. MCCOMBIE

The Principles of Electrophoresis

R. AUDUBERT and S. DE MONDE

(*viii + 142 pp; 9¼ × 5¾ in.*)

London: Hutchinson. 25*s*

WITHIN the past twenty-five years practical electrophoresis has experienced what may aptly be termed a biological revival. Since the considerable development of the moving boundary technique by Tiselius, some two decades ago, and its application by him to protein systems, refinement of the optics has continued and its application progressively widened. However the gram or more of often hard won material required for a full analysis, the limited separation of components from mixtures and the expense of the equipment have all been factors limiting its general use. In the past decade, electrophoresis on paper or in other supporting media has made the separation of both milligram and decagram quantities possible at relatively little expense, but with some loss in other respects such as the evaluation of mobility values.

The major part of this book (90 out of 120 pages) fulfils the claim that it gives a clear introduction to the above developments and deals with some apparatus, techniques and illustrative applications in some detail. Thus far the book will admirably serve the needs of many who wish to become acquainted with and apply the techniques described.

The book has some deficiencies however. No account is given of the increasing application of micro-electrophoresis to the study of the surface properties of 1μ to 10μ particles, ranging from inorganic suspensions to bacteria, yeasts, blood cells and other colloidal organisms. The most serious deficiency is the inadequate account of the theory of electrophoresis and its continued development. The only limiting equation given is that for small particles and large double layers due to Debye and Hückel, $u = D\zeta/6\pi\eta$; no mention is made of the Smoluchowski equation for the large particles and small double layers, $u = D\zeta/4\pi\eta$, or of the transition between them evaluated by Henry. Nor is reference made to the Debye–Hückel approximation $e\zeta/kT < 1$, or to the several effects of relaxation, surface conductance and particle conductance and shape. A brief overall account of present theory, together with a clear statement of the experimental conditions under which electrophoresis yields the most certain quantitative results, would have made a more balanced book and one of wider appeal.

H.W.D.

A Manual of Mathematical Physics

P. I. RICHARDS

(*xi + 486 pp; 10 in. by 7 in.*)

London: Pergamon Press. 55*s*

THE field to be covered by a text devoted to Mathematical Physics is enormous. It was in the old days, and since the dogma must now include Quantum Physics, Matrix Mechanics and Group Theory it is a formidable task to comprehend a reasonable spectrum of the whole within the covers of one book. The author has wisely called his book 'A Manual of Mathematical Physics'. By this means he serves notice that the treatment of topics will be condensed and indeed brisk and that his work is primarily to be regarded as a source or reference book. In spite of this there is a wealth of information. For instance it is a feat to encompass Statistical Physics in 61 pages and a merit to have the field surveyed as a whole.

The chapter headings indicate the scope: Mechanics, Thermodynamics, Electromagnetic Theory, Relativity, Quantum Mechanics, Statistical Physics, Algebra, Differentiation and Integration, Infinite Series, Vector Analysis, Determinants, Matrices, Functions of a Complex Variable, Integral Transforms, Ordinary Differential Equations, Partial Differential Equations, Integral

Equations, Variational Problems and Linear Programming, Unitary Spaces, Eigen-value Problems and Perturbation Theory, Probability and Same Theory, Tensor Analysis, Group Theory.

No specialist in any particular field will be entirely happy with the treatment; the purpose is not exhaustive but comprehensive. As the publishers suggest 'The book might well be defined as a dictionary of terms and concepts with, however, continuity maintained by a series of comments and derivations'. It is, however, more than a dictionary and offers both a survey and guide. If the attempt is made to read the book, surely indigestion will follow. It should be used as a survey and as a survey there is offered a description of the state of the art. It must be used in conjunction with specialist monographs.

There are some strange omissions; there is no entry in the index under meson or under nucleus; the Néel temperature is indexed but antiferromagnetism is not though there is a short paragraph on it. In a first edition of less than 500 pages some of this is inevitable. Little more than a thorough grasp of elementary calculus is assumed but the elementary reader will, of course, require great stamina. G.K.T.C.

Evolution of Nervous Control from Primitive Organisms to Man

A Symposium from the Section of Medical Sciences of the American Association for the Advancement of Science

(Ed) ALLAN D. BASS

(vii + 231 pp; 9¼ in. by 6 in.)

Washington: American Association for the Advancement of Science (publication No. 52, 1959); London: Bailey Bros. and Swinfen. 52*s*

A BOOK of this size cannot cover the ground at a level easily intelligible to the reader unfamiliar with part of the field and most of the terminology. The sections are concerned successively with the Basis of Development and Behaviour in Organisms, Chemical Inducers, Comparative Neurophysiology, Evolution of Nervous Conduction, Neurohumoral Agents, Drug Effects on Higher Animal Behaviour, Chemistry of the Brain, Behaviour Alterations after Cerebral Lesions in Man, and Psycho-Analysis and Human Behaviour.

Each one of these sections is written by a recognized authority in a topic of great complexity and rapid expansion, and if the chapters appear uneven in their content, this reflects on the difficulty of various aspects of neurophysiology rather than on the authors.

It is always difficult to prepare a balanced assessment of symposium material, and it can fairly be said that this is a valuable publication of its type, excellently produced as regards presentation and illustrations. It can be highly recommended as a short review of several important facets of neurobiology for those who wish to refresh and bring up-to-date a background allied to but without their immediate neurological studies: an expert may well be familiar with all the material in one or two chapters and yet certainly profit by the remainder.

The value of each article is enhanced by the addition of a very well-chosen list of appropriate references. A.E.R.

Metallurgy and Fuels

H. M. FINNISTON and J. P. HOWE (Eds)

(ix + 653 pp; 9¼ in × 6 in)

London: Pergamon Press. £7 7*s*

IN THIS series of works on 'Progress in Nuclear Energy' the present book is Volume 2 in Series V. It covers work up to the end of 1957 and comprises twenty-eight papers by specialist authors in Part I and thirteen papers in Part II. In the Preface Dr Finniston states that Part I deals with the metallurgical development of basic materials used in reactors and reports the experiences of various countries in using particular fuel elements in a variety of reactor systems. Part II gives the results of researches in physical metallurgy and solid state physics which may lead to advances and better service control of the metals and ceramics dealt with in Part I. Since Volume 3 is due to be published in 1959 these papers must be looked upon as authoritative detailed progress reports. Each one is preceded by a useful abstract.

The jacket states that the information has been gathered from government, research and industrial laboratories throughout the world. This actually means from NATO countries for it is only in the references given at the end of each paper that a few Russian publications have been noticed.

It is remarked on p. 280 that Britain has backed the gas cooled reactor of the Calder Hall type using uranium fuel in magnesium cans, but 'further development will probably lead to the introduction of beryllium cans, and later, ceramic fuels'. This is a significant statement and the volume includes three papers on beryllium and two on ceramics which are of special interest.

The physical metallurgist will be interested to find thirty-one constitutional alloy diagrams based on the artificial element plutonium, and a review of the uranium alloy systems gives ten diagrams including five new ones. Typical of the more academic papers is one on the 'Kinetics of Transformations of Gamma-phase Uranium Alloys' in which transformation curves are given analogous to those used in studying everyday steels. At the same time there is much information of a technological type, especially as regards the welding of zirconium and its alloys, and the arc melting of this difficult metal to produce ingots. Non-destructive testing of fuel elements is described, including ultrasonic methods, and we learn that ultrasonic impact grinding is suggested for machining beryllium. The cream of the metallurgical world is employed in these new technologies and it is obviously a difficult job to keep pace with the reporting of the tricks which they are devising.

This volume succeeds in giving us a lot of diversified information and the text is accompanied by good line drawings, photographs and photomicrographs. The index of 22 pages is satisfactory. H.O'N.

LETTERS TO THE EDITOR

Electricity Generation from Moving Gas Streams

SIR,

We have read the above article by R. G. VOYSEY* with considerable interest. We think, however, that he is unnecessarily pessimistic in concluding that, in the type of generator using a magnetic field, 'quite high voltages would still be demanded. This almost certainly disposes of the simplest form of ionic generator suggested'.

He says that this conclusion is based on simple arguments of energy balance and that 'the required fractional concentration of ions is approximately ·000043 WM/V. (W is the specific output of the gas in C.H.U.s per pound flow, M is the molecular weight of the substance and V is the voltage of generation.)', (There is a misprint in his paper which gives 0·00043 and his table is in error.) Unfortunately, Voysey has confused flow rates with concentrations.

If N_0 is the number of neutrals flowing per second, the heat input is $N_0 M m_H W$ calories per second, *i.e.* $(Jm_H)\ N_0 MW$ watts (where m_H is the unit atomic mass in g). If, for simplicity, it is assumed that this is converted into electrical power at 100 per cent efficiency (which overestimates the number of ions required) for a given voltage V, the current required is $(Jm_H)\ N_0 MW/V$ amps, which is $(Jm_H/e)\ N_0 MW/V$ electrons per second. Thus, if N_e is the number of electrons flowing per sec,

$$N_e/N_0 = 0{\cdot}000043\ MW/V \qquad \ldots (1)$$

and this is Voysey's result (apart from the misprinted decimal point).

It should be noted that N_0 and N_e are total rates of flow which must be taken across particular areas A_0 and A_e, and since the direction of current flow is always perpendicular to the direction of mass flow, the areas A_0 and A_e are also perpendicular to one another. If the densities (*i.e.* numbers per unit volume) of neutrals and electrons (or ions) are n_0 and n_e respectively, and if v_0 is the velocity of mass flow while v_e is the *transverse* drift velocity of the electrons, then

$$N_0 = n_0 v_0 A_0 \text{ and } N_e = n_e v_e A_e \qquad \ldots (2)$$

Hence

$$n_e/n_o = (N_e/N_0)\ (v_e/v_0)\ (A_0/A_e) \qquad \ldots (3)$$

Now N_0/N_e is the ratio given by Voysey, which depends only on the specific output W, the molecular weight M, and the voltage V, and this is the ratio of *flow rates* given by *Equation 1*. However, the quantity of interest is the fractional *concentration* of electrons (or ions), n_e/n_0, given by *Equation 3*.

Apart from W, M and V, this quantity is dependent upon both the ratio of the transverse electron velocity to the axial velocity, and the aspect ratio A_0/A_e of the device and hence upon its dimensions.

Consequently, it is not true that high voltages are necessarily demanded for the magnetohydrodynamic generator, and the device certainly cannot be 'disposed of' on these grounds. In practice, the generator would be designed to operate at as high a voltage as convenient, both to minimize losses in inversion from d.c. to a.c. (if a d.c. machine were used) and to limit the cathode current density to reasonable values (if a non-inductive type of output were used).

It is true that *seeding* the gas stream by the addition of material such as caesium or potassium 'still leaves the conductivity very low indeed', but not so low that an unacceptably long duct, over which the magnetic field has to be maintained, is required.

We do not understand the implication of Voysey's statement that 'the gas also contains charges of both signs which is useless for this device'. Because of the high mass of the positive ions relative to the electrons, their transverse drift is small, and hence almost all of the current is represented by the transverse drift of the electrons. It is accepted that in order to maintain electrical neutrality a cathode may be needed to replace the electrons which reach the anode (and hence deliver current to the load), but it is difficult to see that the positive ions are 'useless'. Indeed they are essential if neutrality is to be achieved.

Yours faithfully,

K. H. SPRING,
D. T. SWIFT-HOOK

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14th October, 1959

* VOYSEY, R. G. *Research, Lond.* (1959) XII, 246

Reply from Mr R. G. Voysey

SIR,

Mr SPRING and Mr SWIFT-HOOK raise three main queries, *viz.* the misprint, my table's independence of nozzle proportions, and the relative merits of neutral and single-sign charging of the gas. For the first I apologize unreservedly and on the other two points must justify the opinions of my article.

I should also point out that some of the references in the text are wrongly numbered due to the printing dispute preventing me from seeing a final proof. Thus 17 onwards in the text should read 16 onwards and 20 is the 1958 Geneva Conference.

However the misprint of 0·00043 for 0·000043 in the equation was entirely my fault. The error was found before submission (but slipped through to publication) and when the equation was inverted to correct the first column of *Table 1* the amendment was made in the wrong sense. So the figures in this column are 100 times too low. I very much regret this and draw only poor comfort from the small effect on the conclusions. The relative voltage capabilities of the two classes of generator are not determined by ionization requirements and using correct figures, the electromagnetic device will still pay a good fraction of its output for ionization when generating at voltages under 300. In my example the

latter voltage would require a nozzle width in the electric direction of thirty inches, and every inch of this inlet in the magnetic direction would develop about 20,000 kW. The scope for much larger nozzles is obviously restricted and most immediate interest is for much smaller sizes and therefore voltages.

In my article I sought lucidity by avoiding discussion of the nozzle design and by sorting the ionization controlling variables into two naturals groups: (1) the magnetodynamic ones controlling the generated voltage, *i.e.* magnetic field strength, gas axial velocity and the width of the nozzle in the electric direction; (2) the thermodynamic variables implicit in the table which can only be entered after the assumption of a voltage, which is restricted, as I stated, to a few tens of volts per inch of electric axis by practical considerations of field strength and gas velocity. The scarcity ratio of the table is dimensionless and applicable to flow rates or to concentrations only with specified conditions. Applied as a flow rate ratio it gives the minimum ionization sufficient only to supply the ions which are finally collected at a terminal. It ignores the extra ions which have to be produced (and retained in the main stream up to the moment they are lost to exhaust) so as to maintain continuity of current along the electric axis. Your correspondents' analysis can be finished to show that the table does give a minimum ionization as follows:

If N_e is defined by *Equation 1* then *Equation 2* is correct and $N_e = n_e v_e A_e$.

However the total ionization requirements (whether supplied before the nozzle or from the emissive electrode in the nozzle) must total the ion collection at terminals plus the rejection of ions at exhaust, *i.e.*

$$= N_e + n_e \alpha V$$

where α is the area and V the gas velocity.

In my example, the gas increases in volume some eight times in passing through the nozzle and both n_e and the product of αV must vary. It seems possible to assume a design where the combined product approaches $n_e A_0 V_0$ so that

$$\text{total ionization} = N_e[1 + (A_0 V_0 / A_e V_e)]$$

which is never less than N_e.

Even if A_e is made large the fraction in the bracket is likely in practice to be greater than unity as the gas velocity is generally much higher than is the ion drift.

On the issue of neutral plasmas *versus* single-sign carriers there are several reasons for believing that electrons may embarrass operation of the magnetodynamic case.

(*i*) The common claim for electrons of greater 'conductivity' is derived from measurements on electrons, mobile because of their light weight, when urged by various sorts of electric field. In the magnetodynamic generator the current carriers move against instead of with the electric field. The purely electric motions of the electron within the nozzle are circling round the axis of the magnetic field plus slip backwards against the terminals' electric field. Only continual collision by the micro-random and macro-steady motion of the neutral molecules deflects current carriers to the appropriate terminals. A simple argument to remove this doubt (say a co-ordinate transformation to change the dissipative case to the generating case) is not obvious and it would be valuable to have measurements of conductivity with carriers propelled against the field.

(*ii*) With both electrons and ions in the plasma there is continual recombination with thermal degradation of the ionization energy. This resembles an internal leakage path which approaches a short-circuit as the recombination times shorten to the gas transit time. The latter figure is flexible but might be typically one millisecond. I have not seen any calculations to justify much larger recombination times which do not depend either on assuming lower ionization ratios than the magnetodynamic generator requires or simplified assumptions of possible routes by which recombination can proceed.

(*iii*) The neutral plasma suggestion is often coupled with the idea of working the nozzle at just the right temperature to secure thermal ionization according to Saha's equation. There is an immediate difficulty in that the entry and exit to the working section are generous leakage paths and there is also doubt (depending on (*i*) above) about the required temperature. Assuming that the latter is bearable (it may be well above 2000°C) it has been claimed that ionization will be won with heat instead of with electrical energy. When the consequences of the second law of thermodynamics are examined this seems dubious and there is a small doubt whether the device will deliver power when the plasma is in thermodynamic balance with the ionization process. The common assumption that the ion-propulsion processes and the thermal ion-production processes are not strongly coupled is usually based on the high ratios of kinetic velocity to gas velocity and of the latter to the ion drift velocity. To the extent that the ions have a slightly greater velocity than neutral ions there is a tendency to channel the electrical work of the nozzle into further ionization. If the full severity of the second law, together with rapid approaches to equilibrium, is assumed the bulk of the electrical output could be lost in internal heating.

These points make me favour the electrodynamic generator on its better prospects of higher voltage output, lower internal losses and feasibility in very much smaller sizes but I look forward to hearing of experimental work which will confound the above doubts and widen the range of practical forms of ionic generator.

Yours faithfully,

R. G. VOYSEY

Chief Scientist's Division
Ministry of Power
Millbank, London, S.W.1. *2nd November, 1959*

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